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An Investigation of Melt Modulation Science for Enhanced Polymer Product Manufacturing

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AN INVESTIGATION OF MELT MODULATION SCIENCE FOR ENHANCED POLYMER PRODUCT MANUFACTURING

By

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"Success is not measured by what you accomplish, but by the opposition you have encountered, and the courage with which you have maintained the struggle against overwhelming odds."

Orison Swett Marden

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ABSTRACT

The melt modulation concept was originally introduced to control the melt flow during the filling phase of cold runner injection molding machines. Since its inception, several melt modulation systems have been developed. Although previously designed systems successful balanced multi-cavity and family molding parts and controlled weld-line position, they were not commercially viable.

The main objective of this dissertation was to employ scientific and business based approaches to develop and enhance a melt modulation technology for cold-runner based injection molding. This research intends to bridge the gap between an important scientific discovery and its industrial applications. This was achieved with the goal of advancing science and technology to enhance polymer product manufacturing. As a result, a modular melt modulation system was developed to deliver intelligent manufacturing and precision control to cold runner injection molding machines. This modular system has the ability to adaptively manipulate injection molding part qualities and control the melt flow and packing processing parameters during each injection cycle. This precision control is cost effective and results in enhanced production rate, less waste, less processing and set-up time, and better product quality. Also, it has been tested to show that controlling packing parameters contributes to enhancing the final product quality.

This research also focused on manipulating and controlling packing parameters using melt modulation in order to produce molded parts with different optical and

physical properties in each injection molding cycle. Numerical simulations and experimental results of common thermoplastic transparent polymers, such as Plexiglas® V920 (PMMA), LEXAN™ 101-111 (PC), and STYRON® 685D (GPPS) are demonstrated herein.

The work outlined in this dissertation highlights my contributions to the advancement of the science and technology related to multi-cavity injection molding processes as well as the injection molding industry. These contributions included the design and development of a modular melt modulation system to precisely control mold filling and packing pressure and time at the individual cavity level in real-time; and the validation of the impact of packing processing parameters on the quality of injection molding transparent products through numerical simulations and experiments.

CHAPTER 1 – INTRODUCTION AND PROBLEM DESCRIPTION

One of the most utilized manufacturing processes, and sometimes the only practical way to shape complex thermoplastics parts, is injection molding. Almost all thermoplastics and thermoset resins can be injection molded [1]. Injection molding can also be used to produce products from other materials such as metals, glasses, and elastomers, where the material is fed into a heated barrel, mixed, and forced into a mold cavity where it cools and hardens to the formation of the cavity [2].

Standard injection molding machines used today have two main melt delivery systems: hot and cold runner systems. Although hot runner molding has been gaining popularity in recent years, it has only captured an estimated 30% market share [3]. Cold runner systems still dominate having the majority market share in the industry. The injection molding industry has been growing at an estimated rate of 2.8% year over year [4]. In 2010, it was estimated to have a market value of $168 billion [5]. However, like any manufacturing process, injection molding has its own set of capabilities and limitations. The most common cold runner injection molding limitations include the following:

A. Multi-cavity imbalanced filling

B. Difficulties associated with making high quality family molding parts

C. Limited control of weld-line position

D. Inability to control packing parameters during injection molding cycle

Each limitation is discussed in details in the next section.

1.1 Multi-Cavity Imbalanced Filling

One of the limitations of cold runners is the inability to precisely control melt flow during filling process. Even when using geometrically balanced cold runners, the phenomenon of imbalanced filling in the cavities is often observed. This is mainly due to the melt shear imbalance, which results in poor mold quality among the produced parts and often requires additional retooling process. Figure 1-1 shows an example of running a short shot with imbalanced filling in a typical multiple-cavity mold, where the runner was designed in a standard symmetrical and naturally balanced pattern. Manufacturers have long accepted imbalanced cavity filling as a limitation of cold runner injection molding.

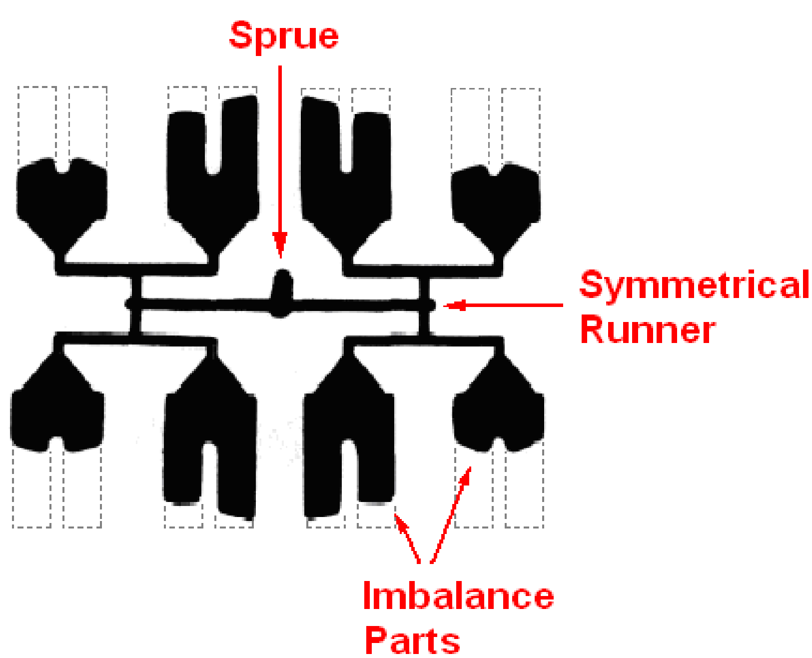


Figure 1-1: Imbalanced Filling in Symmetrical Multi Cavity Mold [3]

1.2 Family Molding

Another common limitation of cold runners is the difficulty in producing family molding parts, which is a process of manufacturing parts of different sizes and shapes within the same mold. Due to the complexity of properly distributing flow and packing pressure between the cavities when using cold runners, family molding is not widely used in the cold runner injection molding industry. A practical example of such failure is shown in Figure 1-2, and the complete part can be seen in Figure 1-3. This short shot occurred during a cold runner filling process for electrical connecter parts produced by family molding. The smaller connectors on the left hand side were completely filled at the same time, the bigger connectors on the right hand side were only partially filled. Incomplete filling is more common when using cold runners, which have little or no control over the distribution of both melt flow and packing pressure.

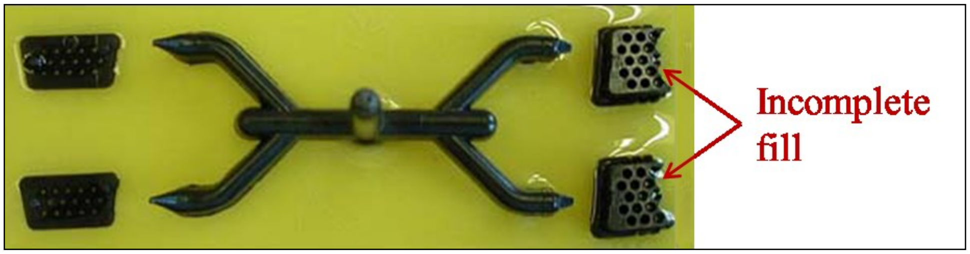


Figure 1-2: Incomplete Filling - Family Molding

Figure 1-3: Complete Filling - Family Molding

1.3 Weld-Line Positioning

The ability to control the weld-line position is another common limitation of cold runner injection molding. A weld-line is formed when two or more melt flow fronts meet in a cavity during a filling process. Typically, the material molded in this region has poor bonding properties (inhomogeneous bond), which makes it vulnerable at high stresses. If the dog-bone specimen in Figure 1-4 is subject to high stress, the part will most likely to break at the weld-line position since this represents the weakest bond.

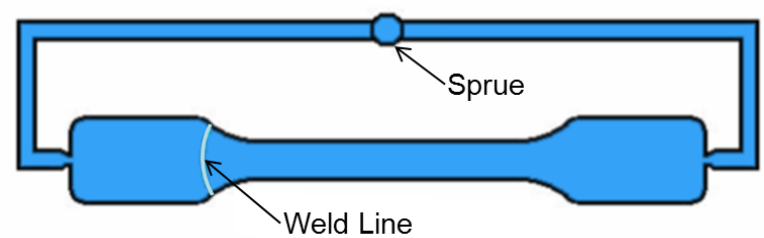


Figure 1-4: Weld-Line Position

1.4 Packing Processing Parameters

The lack of direct control of the packing processing parameters (packing pressure and packing time) and the melt temperature during a cold-runner injection molding cycle is very common. Not being able to control either parameters means that the final part quality is dictated by the preselected control settings prior to each cycle.

Pressure and temperature profiles during an injection molding cycle are very useful and can reveal valuable information about the final part quality. As the injection molding cycle begins, the cavity pressure increases sharply to a peak; this usually indicates that the part is filled. At the end of the filling stage, the part is packed at a specific preselected pressure profile. The shape of the pressure curve is also indicative of the material being processed [28]. Figure 1-5 illustrates typical cavity pressure and temperature history of an injected molded part.

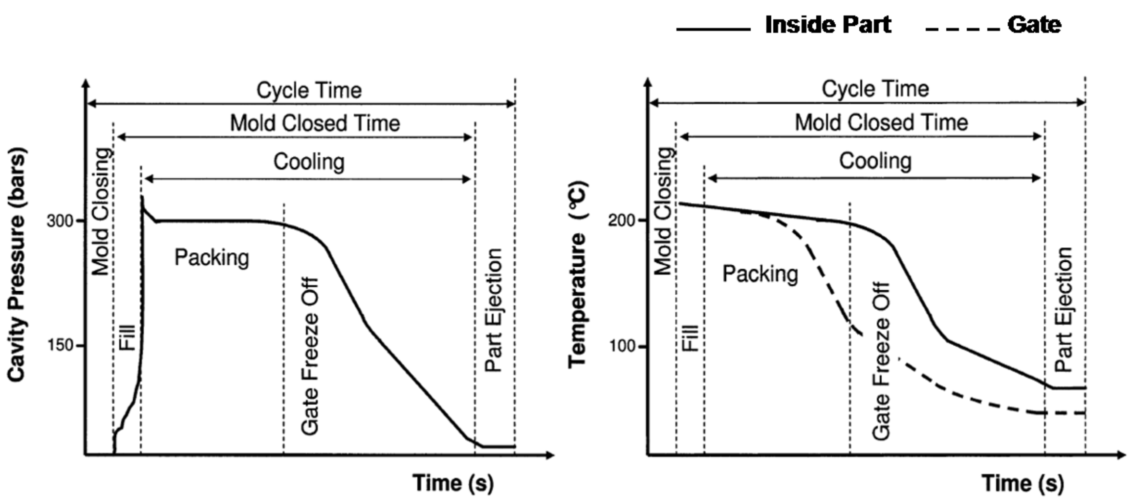


Figure 1-5: Typical Cavity Pressure and Temperature History in an Injection Molded Part [28]

When the cavities are filled at the end of the filling cycle, the packing phase begins. In this phase, melt shear thinning behavior has little or no significant effect and the viscosity of the polymer depends only on the temperature of the melt. When the polymer begins to cool and solidify, it can lose significant volume due to shrinkage attributed to phase transformation from liquid to solid; and, the distance between molecules is effectively decreased. In some cases, the volumetric shrinkage at zero pressure can be as much as 20% or even higher, which often causes poor part quality [3]. To reduce the high volumetric shrinkage rate and ensure flow is compensated through the cavities, the pressure during the packing phase must be maintained to compensate for the lost volume from shrinkage until the gate freezes [30]. As a result, increasing the cavity packing processing parameters (packing pressure and packing time) increase the flow creep to compensate for the lost volume, which also increase molecular orientation, particularly near the gate. Moreover, higher packing processing parameters decreases melt relaxation, allowing increased retention of flow-induced residual stress [31]. Consequently, packing processing parameters have significant impact on polymer molecular orientation as well as mechanical and optical properties of clear polymers during molding.

The best and most cost effective solution to overcome these limitations is through the implementation of melt modulation technology. The melt modulation technique is simple and powerful. It offers better manufacturing control for cold runner applications. It also provides the ability to precisely control melt flow in cold runner mold, fill different size cavities proportional to their cavity size, control weld-line position and packing parameters in a single cycle. Because of its ability to precisely control filling and packing pressure parameters, melt modulation has been shown to enhance physical properties of injection molded parts and improve optical characteristics of clear polymers. Although the melt modulation technology was patented in 1999, it has not been adopted in industry. This is mainly due to the fact that the original system, although technically successful, was not commercially viable.

1.5 Melt Modulation Technique

The melt modulation concept was developed by Dr. John Coulter [27] as a new manufacturing control tool for cold runner applications. It incorporates single or multi-controllable mechanical rotary valves that are embedded into the melt delivery system to control melt flow to the mold cavities. The control valve pins are installed into the moveable side of the mold and end at the parting line. The controllable rotation of each valve pin produces the desired flow modulation and packing pressure effects by rotating the valves to a specific angle, θ, relative to the runner. Figure 1-6 illustrates a diagram of a resultant valve in both fully opened and partially closed positions.

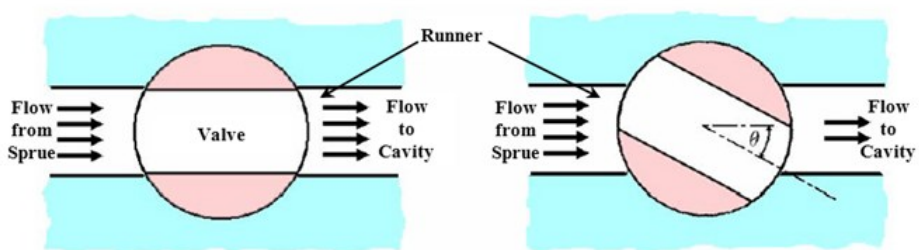


Figure 1-6: Rotary Control Valve Configurations: (a) Fully open (b) Partially closed [29]

A 3-D cross-section view of the original melt modulation control valve in the runner is represented in Figure 1-7.

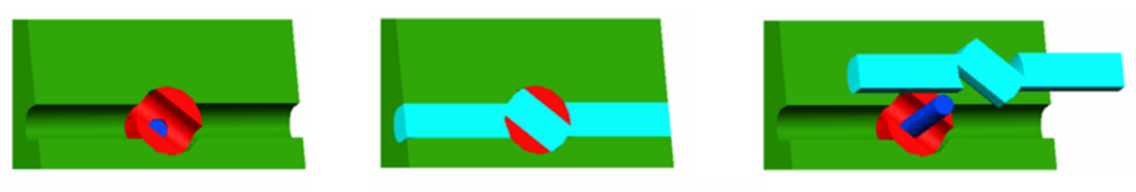


Figure 1-7: 3-D Cross-section View of the Melt Modulation Control Valve in the Runner [29]: (a) Pre-filling, (b) During filling, (c) Part removal

For multi-cavity or family mold cavity filling, the control valves are actuated to adjust for the required amount of flow to fill each cavity. In the case of family molding, the flow to the smaller cavities is more regulated so that both the larger and smaller cavities complete filling at the same time. The diagram in Figure 1-8 shows one control valve is partially closed restricting the melt flow to the cavity, while the other valve is fully open.

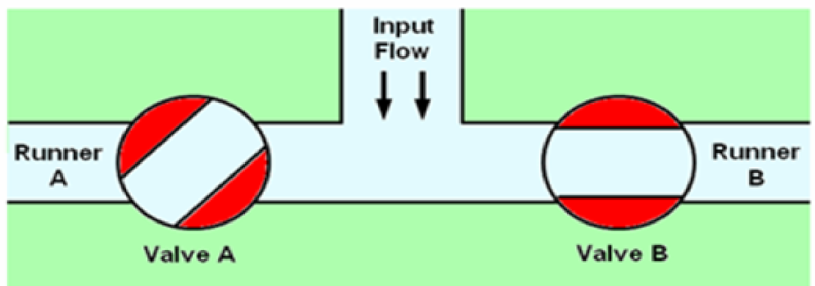


Figure 1-8: Diagram of Melt Modulation Technique [29]

1.6 Research Motivation and Program Objectives

1.6.1 Research Motivation:

The trend throughout the plastics industry is to produce smaller, lighter and more functional systems. This trend, especially in the electronic and computer markets, requires that companies produce a variety of products with smaller and more complex parts and tighter tolerances. It is also expected that production lot sizes in the hundreds rather than thousands or millions will become a commonplace. In addition, reductions in defect rate as low to as 50 ppm will need to be achieved. To meet the demands of global competition, injection molders will need to be in a position to achieve the following [27]:

- Rapidly produce increasingly complex parts
- Have the ability to make smaller batch sizes profitably
- Provide a wide range of products
- Produce improved quality
- Offer lower cost

In order for this trend to be realized, systems with more precise melt flow and packing pressure control would be required. In response to these changes in market place requirements, the melt modulation technique was introduced in 1999.

1.6.2 Program Objectives:

The key goals of this research are as follows:

1. To design and develop an enhanced multi-modular melt modulation prototype with a focus on improved control and commercial viability.
2. To experimentally and analytically validate the enhanced system for novel differential control of filling and packing during injection molding.
3. To scientifically analyze and validate the benefits of a multi-modular system.
4. To complete a thorough engineering analysis exploring the practical business aspects of the new multi-modular system.

1. To design and develop an enhanced multi-modular melt modulation prototype with a focus on improved control and commercial viability.

Prior to developing the modular melt modulation system, previously designed systems had been thoroughly analyzed and studied. Based on the review of previous systems, technical specifications and objectives were established. The modular melt system prototype was designed and developed to be equivalent to a Technology Readiness Level 6 (TRL6), as defined in Figure 1-9. Since the application of the modular melt modulation is industrial, the prototype was only approved in an industrial environment.

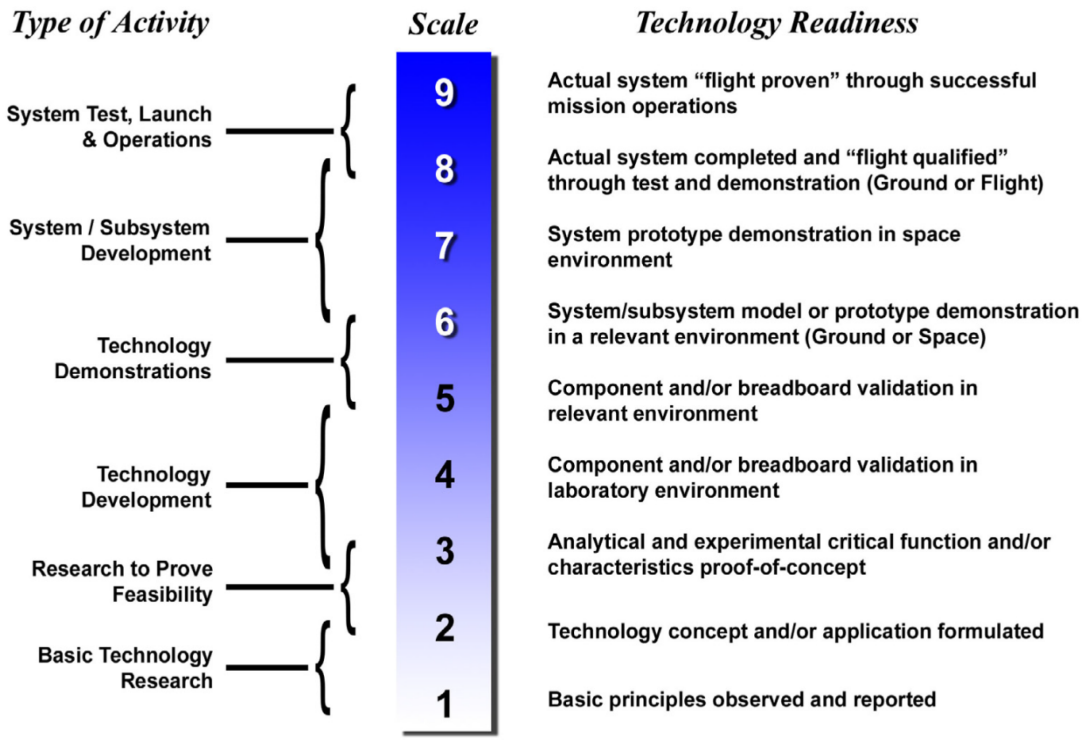


Figure 1-9: Definition of Technology Readiness Level for the Aerospace Industry [62]

To minimize market entry barriers, the design of the modular prototype system was simplified to reduce cost, while still utilizing high quality components. The finished prototype can be marketed to retrofit existing cold runner injection molding machines and to companies that are currently producing new injection molding equipment. The primary target market focuses on cold runner injection molders that require precession and family molding for small parts that are used in the electronics, nanotechnology, dentistry, optics, medical devices, energy products, and aerospace industries. The markets that would benefit most from this technology are those producing low volume (less than 100,000 parts annually) and short runs on cold runner injection molding machines.

2. To experimentally and analytically validate the enhanced system for novel differential control of filling and packing during injection molding.

The modular melt modulation system was validated experimentally and through numerical simulations as well.

i. Analytical Validation:

Numerical simulations of three common optical polymers have been performed to investigate the effect of cold runner injection molding packing processing parameters on final product quality. The materials selected for the analysis were Polymethyl Methacrylate (PMMA), Polycarbonate (PC), and General Purpose Polystyrene (GPPS). PMMA has a trade name of Plexiglas® V-920 and is manufactured by Arkema, Inc. Polycarbonate (PC), known as LEXAN™ 101-111, is manufactured by SABIC. General Purpose Polystyrene (GPPS) is made by Americas Styrenics and also called STYRON® 685D. Results showed that there is a direct link between packing time and packing pressure and the molecular orientation of a clear polymer. Turning any one of the valves during an injection molding cycle typically results in pressure drop across all valves. This pressure change impacts the final optical properties and physical characteristics of the molded parts.

Control valve linear distance from the sprue is another variable that was investigated. Additional analysis was conducted to investigate the optimal location for the control valve. Numerical simulations showed that pressure drop slower near the gate and the sprue and it drops faster between gate and the sprue (see Figure 1-10).

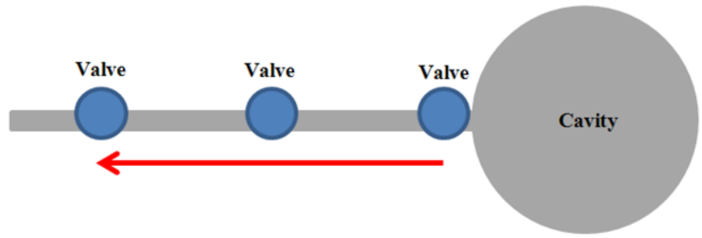


Figure 1-10: Different Valve Locations Relative to the Mold Cavity

ii. Experimental Validation:

The same three common clear polymers were chosen for the experimental validation. ASTM D638, type I and type IV, dog-bone shape parts were used to investigate the effect of the packing processing parameters on molecular orientation during injection molding cycles. Testing results showed that changing the packing pressure and packing time had a direct impact on the final product optical quality in terms of both precision of geometric dimensions and optical birefringence. Increasing packing processing parameters tends to reduce volume loss (shrinkage) and deflection. However, it increases the product final weight. In addition, increasing packing pressure and packing time causes higher molecular orientation, which is evidenced through higher birefringence and optical retardation. Products with higher molecular orientation in the flow direction exhibit higher tensile strengths. However, high birefringence causes poor optical characteristics such as haze or focal blur.

3. To scientifically analyze and validate the benefits of a modular system

The benefits of the modular melt modulation system were validated through numerical simulations and experimental testing. Numerical simulations and experimental results of an ASTM D638, type I, dog-bone shaped parts showed that optical properties and physical characteristics of polymers in cold runner injection molding are sensitive to changes of packing processing parameters. Additional simulations and testing were performed on ASTM D638, type IV, using the modular melt modulation system. The results showed that turning the control valves of the modular system modulated the melt flow through the runner and balanced filling of all cavities in a multi-cavity mold. It also showed that turning the valve during an injection molding cycle changed the pressure drop across the valves, which had direct impact on the molecular orientation of the final product. As a result, the final product quality can be manipulated directly by the modular melt modulation system.

4. To complete a thorough engineering analysis exploring the practical business aspects of the new multi-modular system

The modular melt modulation system was developed to solve common problems that occur in cold runner injection molding. The modular system was designed to meet the technical specifications, but also be commercially viable. Market research and financial analysis were performed to ensure there is a potential opportunity for the modular melt modulation system. Several case studies were analyzed comparing cost of ownership to the benefits received including the cost savings resulting from incorporating the modular melt modulation system.

1.7 Dissertation Structure

This dissertation presents the design, development and validation (analytical and experimental) stages of the new modular melt modulation system. This document consists of nine chapters, including the introduction, and is structured as follows:

CHAPTER 2 details relevant technological background, including information on cold and hot runner based injection molding; potential opportunity for the melt modulation technique in the injection molding industry; and the history, capabilities and limitations of the melt modulation technique.

CHAPTER 3 describes related scientific and technical fundamentals of melt rheology, control valves and their significance; and the analytical control technique I utilized.

CHAPTER 4 presents my design and development of the new modular melt modulation system as a workable prototype for market evaluation.

CHAPTER 5 and CHAPTER 6 illustrate numerical simulation results, using Moldflow software, of varying cold runner injection molding packing processing parameters with and without melt modulation system and their impact on part quality of clear polymers.

CHAPTER 7 contains experimental results of the impact of packing processing parameters and different melt modulation control methods on the final quality of clear polymers.

CHAPTER 8 discusses financial case studies and market research for the modular melt modulation system, with a focus on feasibility of commercialization.

Finally, in CHAPTER 9, conclusions are presented regarding all the work completed toward this dissertation and the impact of this research with some recommendations for future work and suggestions related to the melt modulation technique.

CHAPTER 2 – RELEVANT TECHNOLOGICAL BACKGROUND

2.1 Injection Molding

Injection molding is the most utilized manufacturing process for thermoplastic and thermosetting materials. Sometimes, injection molding is the only practical process to shape complex thermoplastic parts. However, it can also be used to produce products from other materials such as metals, glasses, and elastomers, where the material is fed into a heated barrel, mixed, and forced into a mold cavity where it cools and hardens to the formation of the cavity. A standard injection molding machine, illustrated in Figure 2-1, consists of the following three main functional units:

1. Injection Unit
2. Mold Assembly
3. Clamping Unit

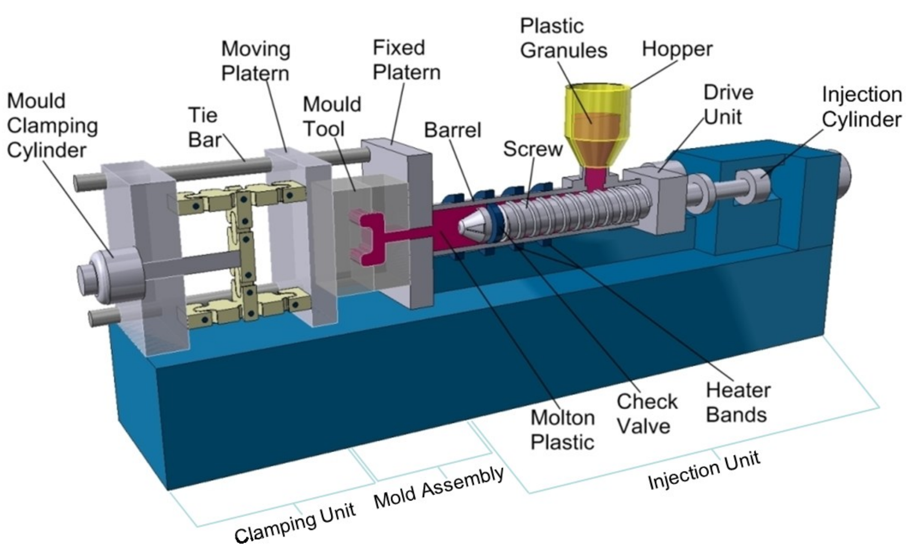


Figure 2-1: Injection Molding Machine [64]

The injection process liquefies the plastics before injecting or advancing the resin into the mold cavities. The clamping unit holds the mold together while the resin is being fed into the mold cavities and the resin is cooled [1].

The ideal injection molding system delivers high quality molded parts of uniform density, which are free from all physical and cosmetic defects at the best possible cost. However, every technology has its own capabilities and limitations. Common molding defects in injection molding include the following:

1. "Short shot" – caused by incomplete filling
2. "Sink marks" – caused by low packing pressure
3. "Jetting" – caused by high speed injection
4. "Warpage" – caused by uneven cooling
5. "Burn marks" – caused by poor removal of air

Within the mold assembly, the melt delivery system is the second major unit of an injection molding machine, and plays a major role in the final product quality. Its primary functions are as follows:

1. Contain the polymer melt within the mold cavities until the cavities are completely filled, packed and cooled.
2. Efficiently transfer heat from the hot polymer melt to the cooler mold steel, to ensure uniform product.
3. Eject the molded part.

The main components of the mold assembly are the mold core and the mold cavity, which are typically made of steel or aluminum and highly customizable tooling. There are different types of mold configurations (i.e. two-plate, three-plate, etc.) and each design is utilized for a different purpose depending on machine type, part configuration, mold capabilities and limitations. Given its simplicity, the two-plate mold is more popular. As shown in Figure 2-2, the two-plate mold consists of two main sections, the stationary and moveable plates. The stationary half includes the top clamping plate and the “A” plate. The moveable half consists of the “B” plate, support plate, ejector plate, the ejector housing, and the supporting hardware. During the injection cycle, the part cavity (the space between the mold core and the mold cavity) is filled with molten plastics to form the desired part.

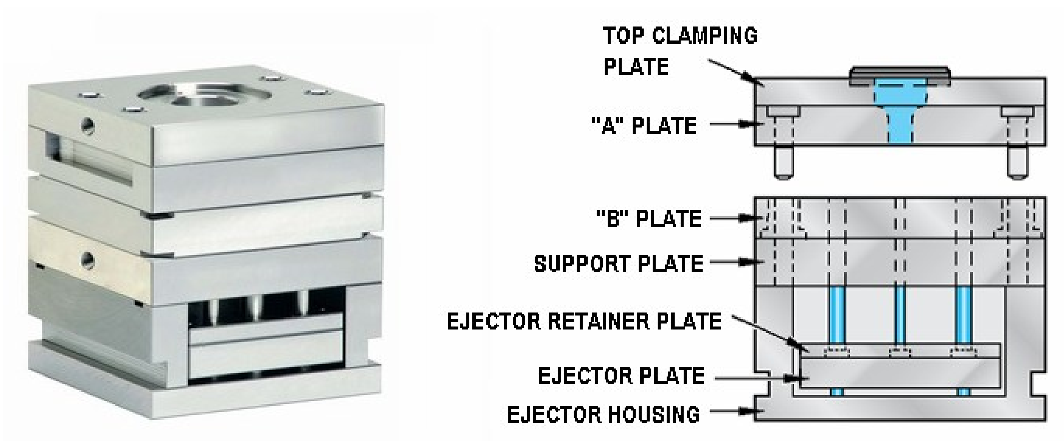


Figure 2-2: Two Plate Mold Base Configuration (Source: DME electronic catalog)

The three-plate mold assembly, shown in Figure 2-3, is very similar to the two-plate mold, but not as common. A three-plate mold has multiple runners so it can provide more gating location flexibility than the two-plate mold. Also, the separation of the feed system from the mold cavities are often automated, which saves time and cost. However, three-plate molds are more complex and have more potential issues than a two-plate mold, including the following: [7]:

1. Cold runner is molded and ejected at the end of each cycle. Large runners (compared to molded parts) lead to increased material consumption and cycle time, thus increasing the molded part cost.
2. The mold requires additional plates and components, which increases cost and complexity.
3. The mold requires a large mold opening stroke to eject runner.

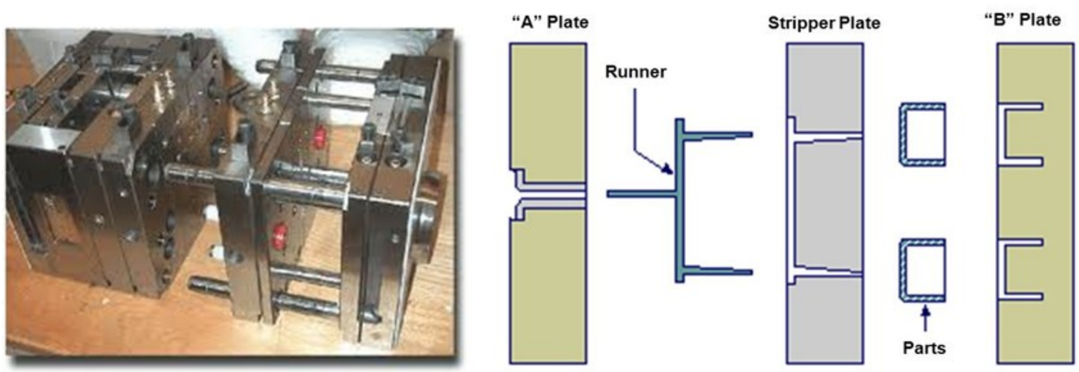


Figure 2-3: Three-Plate Mold Assembly [8]-[9]

Applications for cold runner and hot runner systems sometimes overlap. Choosing the appropriate system delivers high quality product at the best economic value. Selecting one system over the other for specific applications is usually based on some of the following factors [10]:

- Cost of investment and the return on capital
- The complexity of the part needed to be injection molded

- Color requirements - the range and frequent changes of color during each production run
- Final physical and optical characteristics of the finished product
- Type of resin material to use - virgin or "regrind"
- Single or multiple design production
- Volume of parts to be produced
- Production speed required

The electrical/electronics industry has benefited from hot runner systems to produce small components (connectors and bobbins that are molded in multi-cavity molds) in a high volume production. Also, companies manufacturing large multi-gated parts for the automotive industry (bumpers and dashboards) have benefited from the cost and technical advantages of hot runners. In other cases such as low volume production, cold runners might be the best tooling. The capabilities and limitations of hot runner and cold runner systems are briefly identified below.

2.2 Hot Runner vs. Cold Runner Melt Delivery Systems

This section provides a comparison between two common melt delivery systems (cold and hot runners systems).

2.2.1 Hot Runner System

The hot runner system (also referred to as a hot-manifold or runnerless system) was first developed in the early 1940's. However, because of reliability setbacks and high initial investment cost, the process did not gain popularity until the early 1990's, when technological advances and lower energy and higher raw material costs made it economically feasible. A patent that dates back to 1940 for a hot runner system was issued to E. R. Knowles [11].

Figure 2-4 shows a schematic drawing of an early design for a hot runner mold by Robinson Plastics Corporation.

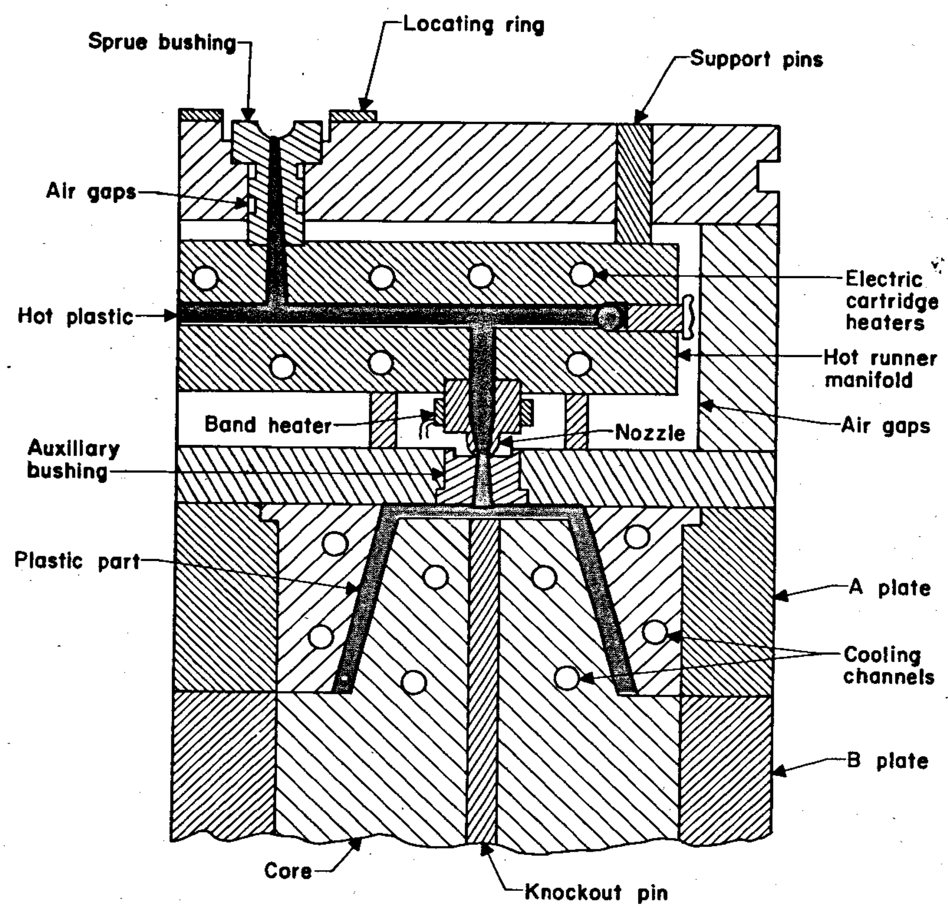


Figure 2-4: Schematic Drawing of an Early Design Hot Runner Mold (Robinson Plastics Corp.) [11]

Hot runner systems provide consistency in material flow and fill from part to part. They consist of two plate molds with a heated melt delivery system inside one half of the mold. The runners in the injection molds are kept hot and insulated from the chilled cavities. The main components of a hot runner system are the manifold and the drops [12].

There are several different types and combinations of hot runner systems which are now available 'off-the-shelf'. The most common are the standard hot runners and the insulated runners. Standard hot runners are divided into externally heated and internally heated runners. The former has been in use much longer than the latter [13]-[14]. Unlike cold runner systems, hot runners keep the polymer in a molten state and are not ejected with the molded part. The polymer is kept in a liquid state at approximately the same temperature and viscosity of the material in the barrel of the injection molding machine. In insulated runners, the polymer in the middle of the runner is fluid, but the outer part is solidifies. Figure 2-5 below shows the hot runner system types.

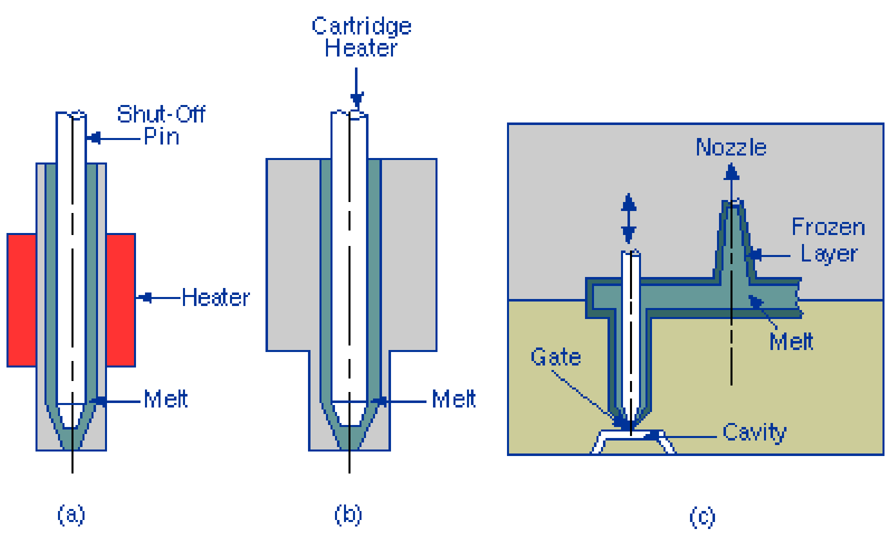


Figure 2-5: Hot Runner Types - (a) Externally Heated, (b) Internally Heated, and (c) Insulated [14]

i. Externally Heated Manifold/Nozzle Systems:

An externally heated runner system consists of a cartridge-heated manifold with interior flow channels. The manifold is typically designed with various thermal insulating features to separate it from the rest of the mold, thus reducing heat transfer (loss) [14]. Because there is no heater obstructing flow and the polymer is kept fluid, externally heated hot runner channels have the lowest pressure drop of any runner system. This makes them a better candidate for color changes, when compared with other types of hot-runners, since none of the polymer in the runner system freezes. However, externally heated nozzles have more limitations than those of internally heated systems. An externally heated nozzle has heating elements (thermocouple, heating coil, sleeve, etc.) located on the outside of the nozzle's body. This causes expansion when the coil is heated pulling away from the nozzle's body, creating a gap, and the coil no longer touches the nozzle body uniformly. This creates the need for a higher temperature to properly heat the polymer, which will increase the risk of uneven heating, overheating and burning out the coil. Yet, this system is better for processing thermally sensitive materials since there are no places for material to get trapped and degrade [12].

ii Internally Heated Manifold/Nozzle System:

Compared with externally heated runners, internally heated manifold is a relatively newer system. The main goal of its development was to reduce maintenance cost, where the internally heated nozzle is 100% sealed, reducing the need for spare parts replacement. Internally heated runners supply the heat through a system of heat tubes or probes located within the flow channels. The nozzle heating elements (the thermocouple, heating coil, sleeve, etc.) are located much closer to the gate, delivering heat at a very precise temperature. As a result, a better heat profile and more controlled melt temperature lead to better molded part quality [12].

The drops offer optimal gate tip control. They separate runner heat from the mold, which reduces heat transfer (loss) to the rest of the mold. This is because an insulating frozen layer is formed against the steel wall on the inside of the flow channels [12]-[14]. However, internally heated runners require higher molding pressures than external heating and color changes are very difficult. Furthermore, they are not recommended for thermally sensitive materials since such runner configurations are prone to material degradation.

iii Insulated Runner System

Insulated runner mold is a special type of hot runner system that is not heated, where the manifold is run at ambient temperature. The runners have oversized and extremely thick flow channels formed in the mold plate and stay molten during constant cycling. These flow channels are large enough to ensure a material flow due to the insulating effect of the outer skins (frozen on the runner wall) of solid and semi-plasticized material. In this system the nozzles are generally internally heated. Compared to hot runners, this system is very inexpensive and ideal for low tolerance parts such as plastic cups and Frisbees. Nevertheless, these runner systems have major limitations. They offer little or no control, and only commodity plastics like PP and PE can be used. Also, if the runner system freezes due to stopping the mold cycling, the mold has to be split in order to remove it [12]-[14]. For those reasons, hot runners (internally and externally heated) are more commonly used than insulated runners. Table 2-1 details some of the advantages and disadvantages of the three hot runner systems.

Table 2-1: Advantages/Disadvantages of Hot Runner Systems [14]

Runner Type	*Advantages*	*Disadvantages*
Externally Heated	➢ Improved distribution of heat ➢ Better temperature control	➢ Higher cost ➢ Complicated design ➢ Thermal expansion of various mold components
Internally Heated	➢ Improved distribution of heat ➢ Better distribution of heat ➢ Reduced maintenance cost ➢ Improved part quality	➢ Higher cost ➢ Complicated design ➢ Thermal expansion of various mold components ➢ Requires careful balancing and sophisticated heat control
Insulated	➢ Less complicated design ➢ Less costly to build	➢ Undesired freeze-up at the gate ➢ Requires fast cycle to maintain melt state ➢ Long start-up periods to stabilize melt temperature ➢ Problems in uniform mold filling

Depending of the requirements of the final product, a hot runner system may or may not be the best option. For a blemish-free surface, hot runners may be the only choice. For other parts configurations that require less startup difficulty, more simplicity in the mold control system and less mold construction cost may rule out hot runner systems [15]. However, when selecting a hot runner system, the factors in Table 2-2 should be considered.

Table 2-2: Selection Criteria for a Hot Runner System [16]

Economy	*Product*	*Process*	*Material*
○ Investment	○ Dimensions	○ Start up	○ Flow behavior
○ Production quantity	○ Shot weight	○ Total flow path	○ Melting temperature/range
○ Cycle time	○ Gate/sink marks	○ Pressure distribution	○ Process window
○ Material waste	○ Reproducibility	○ Melt homogeneity	○ Thermal stability
○ Energy	○ Tolerances / warpage	○ Residence time	○ Reinforcement
○ Regrinding	○ Fiber orientation	○ Color change	○ Additives

2.2.2 *Cold Runner System*

Cold runner molding has the majority market share primarily because of its simplicity and low investment cost [3]. It is easier to operate, manage, and maintain. A material is injected into cavities through a runner profile, cooled, solidified and then ejected at the end of every molding cycle.

For detailed comparison between the two runner configurations in terms of the capabilities and limitations, see Table 2-3.

Table 2-3: Capabilities and Limitations of Externally Heated Hot Runner and Cold Runner Systems [3], [10]-[13], [15]-[22]

Criteria	Cold Runner Molding (70% Market share)	Hot Runner Molding (Externally heated) (30% Market share)
Overview	➢ Runner (excess material retained in the feed channels) is cooled and ejected with the part ➢ A part and a runner are produced every cycle ➢ Waste material must be either disposed of or reground and reprocessed	➢ Hot runner molding usually yields the lowest cost per finished part, but the molds can be very expensive to build. ➢ Molds have heated manifold & nozzles. ➢ No runner (hot runner eliminates the excess material retained in the feed channels of a cold runner mold)
Best for:	➢ Short runs ➢ Simple design parts ➢ When more than one color part need to be produced	➢ High volume and long production cycles ➢ Highly complex design and automated production ➢ Molding expensive polymer ➢ Family molding
Cost	➢ Less Expensive ➢ (Cost of the Machine)	➢ More expensive. ➢ Typically, the cost of the machine, cost of nozzles and

Criteria	Cold Runner Molding (70% Market share)	Hot Runner Molding (Externally heated) (30% Market share)
		supporting equipment.
Material Loss	➢ Runner ➢ Rejects	➢ Rejects only
Operating Cost	Lower	Higher
Maintenance Cost	Lower	Higher
Initial Start-up Cost	Lower	Higher
Advantages	➢ **Lower investment –** Major advantage ➢ **Simplicity** – Simple mold design ➢ **Lower costs -** manufacturing, operation and maintenance. Less expensive to build, operate and maintain than hot runners ➢ **No high skill-level** personnel are required for maintenance ➢ **Flexibility** – Tolerant of all plastic materials ➢ **Faster start up -** Start up procedure is more easier and quicker ➢ **Less Downtime** – No electrical systems such as cartridge heaters burn out and connecting wires fails ➢ **Shorter Downtime** – it takes less time to fix when the mold is down for repairs. ➢ **Simpler mold repair** – compared with hot runner molds ➢ **Color change** – Easy changes ➢ **Consistent operation**	➢ **Family Molding** ➢ **High Volume Productions -** economical for production of over 50,000 parts per year (most cases) ➢ **Material savings -** no material loss from regrind or reprocess ➢ **Low cost / piece -** least expensive for large volume production ➢ **Shorter, faster cycle times -** no runners to cool ➢ **Automated processing –** No need to separate runners from the parts ➢ **No Material Contamination -** Reduces the possibility of contamination from regrind ➢ **Lower pressure –** both injection and clamping pressures ➢ **Shorter cooling time –** no runner ➢ **Shot size reduced - reduced**

Criteria	Cold Runner Molding (70% Market share)	Hot Runner Molding (Externally heated) (30% Market share)
		shot volume into runners ➢ **Cleaner molding process -** no reground sprues and runners are left at the end of each cycle ➢ **Reduction in material shear** ➢ **Improved part finish -** blemish-free surface ➢ **Balance molding -** less sensitivity to the requirements for balanced runners ➢ **No blending cost** of regrind with virgin material or for material handling ➢ **No Material Waste** - reduction of scrap (limited to rejected parts), permitting a much higher percentage of virgin material in the part, which maintains a better level of physical properties ➢ **Better Physical Properties -** No degradation of material properties, especially when running clear materials ➢ **Better dimensional Control** - because material temperature and pressure in the cylinder are the same, there is consistent heat within the cavity, resulting in better parts and fewer rejects. ➢ **Quality Improvement** ➢ **Effective increase in shot capacity** - especially multi-cavity molds ➢ **Energy Saving -** no energy wasted on melting, cooling, and regrinding the runner, which is sometimes 50% of the shot. ➢ **Easing Compliance with**

Criteria	Cold Runner Molding (70% Market share)	Hot Runner Molding (Externally heated) (30% Market share)
		OSHA Regulations - reduction of noise and dust caused by regrinding, cycle time is reduced in cases where runners take longer to freeze than molded parts ➢ **Improving Productivity -** cold runners no longer catch on knock-out pins, leader pins, or hoses during automatic molding, where automatic runner-removal systems can fail and cause mold damage ➢ **Reduced Sink Marks** ➢ **Simplified Multiple Gating** especially for large parts ➢ **No Finishing Required –** especially for the gate, which is sheared automatically. This saves labor and handling, and reduces the loss of material caused by additional operations such as milling ➢ **Minimum Pressure loss** via the sprue-runner system ➢ **Faster Cavity Filling -** elimination of pressure and time loss in filling a runner system permits the mold to fill faster, which is particularly helpful in thin-wall moldings ➢ **Even Cavity Filling** - there is an even start in filling the cavities ➢ **Minimum Operator Attention** – A human operator is always required, but the operator can run other machines or perform other tasks such as inspection and packing

Criteria	Cold Runner Molding (70% Market share)	Hot Runner Molding (Externally heated) (30% Market share)
		➢ **Less propability of Gate Freezing -** this permits more freedom in molding conditions ➢ **Multiple Use of Tooling -** controls, and occasionally manifolds, and nozzles can be used on more than one mold, which significantly reduces the cost of tooling
Disadvantages	➢ **Simple Mold Design** ➢ **Waste Plastics Generated** ➢ **Regrind of Runner Material –** excess material must be disposed of or reground and reprocessed ➢ **Material contamination** is possible due to material regrind ➢ **Additional Steps** – secondary operations in the manufacturing process may be required ➢ **Lack of Melt Control** - no melt flow control during filling process ➢ **Lack of Packing Pressure Control** - no cavity pressure control during the injection molding cycle ➢ **Limited Weld-line Control** ➢ **Possible consequences of Regrind:** ◊ Increases variations in the injection molding process ◊ Detracts from material properties (i.e. strength, mechanical properties, clarity in light pipe or lens production)	➢ **Higher Investment –** Major disadvantage ➢ **Complexity** – the mold design requires more engineering and expertise than a three-plate mold to operate successfully and profitably. If the gates are in the wrong location, a costly time-consuming job is required to fix, and sometimes a complete rebuild of the mold is necessary. If the probes are in the wrong location, accurate machining is required ➢ **High Skill-level Personnel** are required for maintenance ➢ **Slow and Complex Start Up -** start up procedure is more difficult ➢ **Critical Temperature Control -** temperature at the nozzle has to be just right. Too hot can cause Nozzle Drooling, too cold can cause some melt to solidify ➢ **Radiation Heat Loss (Manifold) -** Significant cost factor ➢ **Thermal Expansion** of various components needs to be taken

Criteria	Cold Runner Molding (70% Market share)	Hot Runner Molding (Externally heated) (30% Market share)
		into account ➢ **Critical Molding Conditions** ➢ **Thermal Degradation** of material. Risk of thermal damage to sensitive materials ➢ **Abrasion** (reinforced plastics) ➢ **Frequent Downtime** – more components that are susceptible to failure (i.e. nozzle blockage, electrical systems such as thermocouples and cartridge heaters burn out, and connecting wires fails) ➢ **Longer Downtime** – it takes longer to fix when the mold is down for repairs. Repair normally requires full disassembly, cleaning and reassembly ➢ **Gates are sensitive to clogs** – Even with strainers in line, a slight bit of contamination such as dirt or paper from bags may plug the small gates ➢ **Drool** – Molds without gate valves may drool from time to time especially when the valve is left open for a long time ➢ **Color Change Problems** ➢ **Higher Parts Replacement Costs** - parts more susceptible to: o Breakdowns o Leakage o Heating element failure ➢ **Long Purging Time**

Criteria	Cold Runner Molding (70% Market share)	Hot Runner Molding (Externally heated) (30% Market share)
Common Problems	➢ Unbalanced filling ➢ Cosmetic defects	➢ The part is not filling ➢ Nozzle drooling ➢ Nozzle not working ➢ Excessive flash on part ➢ Burn marks/streaks on part or near gate ➢ Excessive tip wear in nozzles when using plastics with high glass fill content ➢ Gate vestige too large ➢ Gate freezing off too soon, or during cycle ➢ Flow lines on large flat part ➢ Bloom on part opposite gate ➢ Cold slug in part ➢ Intermittent blockage caused by cold slug, tip fails by trying to extrude through nut ➢ Plastics sticking to front of bush nut or sprue nut ➢ **Quality Conditions for Partially Crystalline Engineering Thermoplastics:** ◊ The temperature must be controlled more strictly than in the case of amorphous materials ◊ Very high temperatures will usually cause the polymer to degrade (blistering and other undesirable effects). ◊ Streaks, discoloration and surface defects will also be produced, due to local overheating

Criteria	Cold Runner Molding (70% Market share)	Hot Runner Molding (Externally heated) (30% Market share)
		◊ Pressure: Unsuitable hot runner systems usually cause high pressure losses ◊ Melt residence time can vary between cavities ◊ Separate controls should be provided for the hot runner inlet, the runner and each nozzle, to enable all parts to be individually balanced with regard to the thermally sensitive molding compounds. Regulating devices should be used which guarantee constant temperatures through adaptation of the power supply (e.g. PID) ◊ The bypass inside the runner should be as perfect as possible for materials with high thermal sensitivity such as POM and flame resistant compounds ◊ In general, it is inadvisable to use shut-off nozzles when processing POM. However, if the use of needle valve nozzles is needed to process other kinds of material, the nozzle/needle combinations should be used which keep pressure losses as low as possible

2.3 Previous Scientific Development

2.3.1 Melt Modulation Development

Since its introduction in 1999, melt modulation technology has seen many developments and improvements to make it more practical and efficient for cold runner systems [28]-[29]. It also has been experimentally validated for several filling applications of cold runner based injection molding. Figure 2-6 shows a history timeline of the melt modulation system.

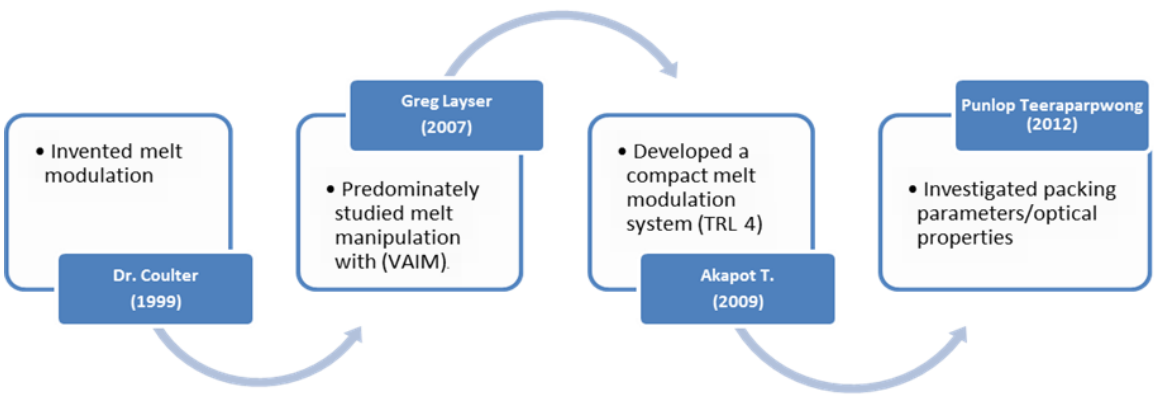


Figure 2-6: Melt Modulation History

Previous work done using melt modulation by Layser [28], [32], [33] and Tantrapiwat [29], [34] demonstrated significant quality product enhancements during the filling phase of cold runner based injection molding, and added capabilities such as balanced multi-cavity molding, family molding, and weld-line position control. Later, Teeraparpwong [35] began expanding the work to investigate the processing parameters and their impacts on optical properties. The goal was to set the stage for expanding the melt modulation capabilities to control packing parameters during the packing phase to enhance product molecular orientation and optical properties.

1. **Dr. John Coulter** invented the melt modulation concept in 1999, as a new manufacturing control tool for cold runner applications. Since then, several melt modulation designs were introduced.
2. **Dr. Greg Layser** predominately studied melt manipulation with vibration-assisted injection molding (VAIM). Figure 2-7 shows a schematic depicting the implementation of VAIM process. He also covered other areas, including:
    a. Numerical Simulation of a Multi-cavity Mold Utilizing Cavity Specific Control of Melt Flow During Injection Molding
    b. Localized Material Effects Associated With Flow Control during Multi-cavity Injection Molding Processes.

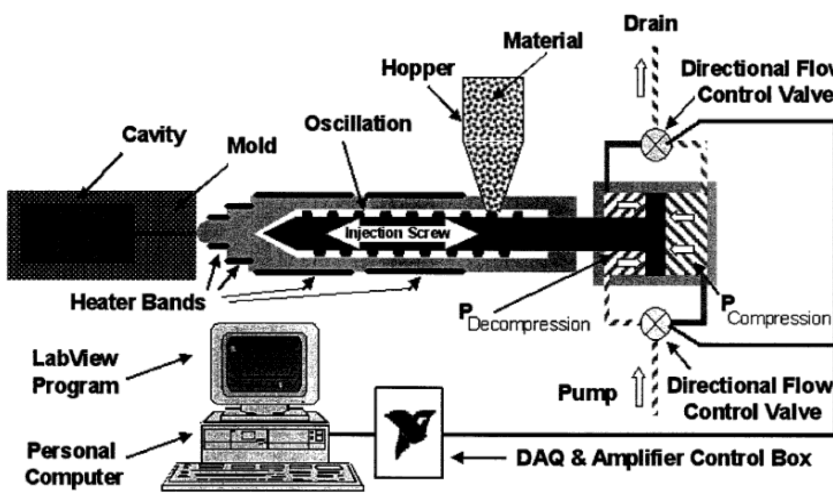


Figure 2-7: Schematic Depicting Implementation of VAIM Process [28]

3. **Dr. Akapot Tantrapiwat** successfully improved the original system, shown in Figure 2-8, and developed a compact melt modulation system that has significant reduction in the system size and cost of original system. His redesign effort focused on:

a. Control Valve

b. Driving Mechanism

c. Controller

d. Control Techniques (Fixed angle, Bang-Bang, and Hybrid)

He also conducted several experiments of molds that have more than 4 cavities using compact melt modulation system.

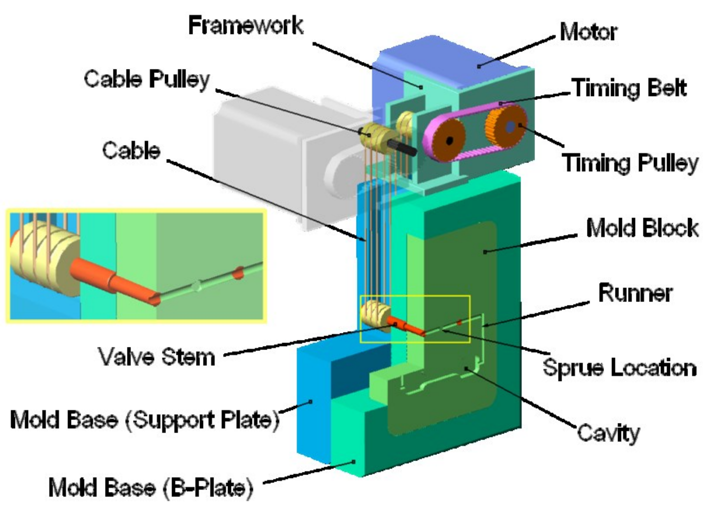
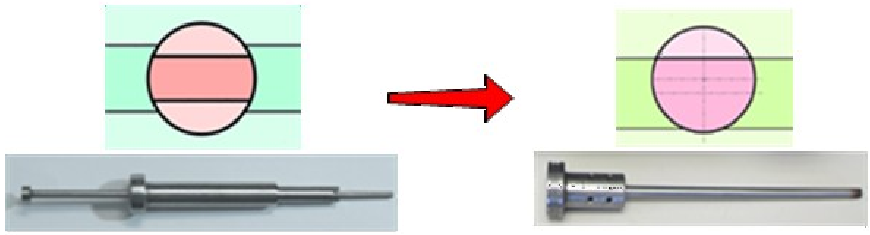


Figure 2-8: Conceptual CAD Model of the Original Melt Modulation System

a. Control Valve:

The original rotary valve, shown in Figure 2-9: (a), was expensive and required an ejector pin to eject the molded parts. Also, because the original valve had limitations such as a small control range, it was changed to an eccentric plug valve, Figure 2-9: (b). This improvement increased the control range, which increased effectiveness and reduced cost.



(a) **(b)**

Figure 2-9: Valve Port Configurations: (a) Rotary (b) Eccentric

The configuration of the new eccentric valve is shown in Figure 2-10. The geometry of the eccentric valve port is similar to the original design, except that it has only one plug and it is installed at a slightly offset location.

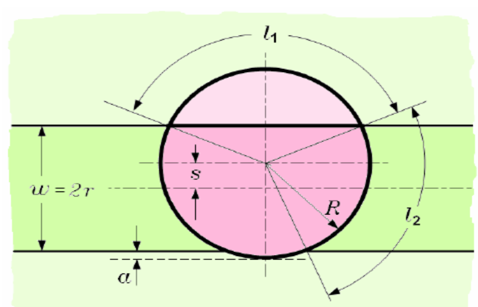
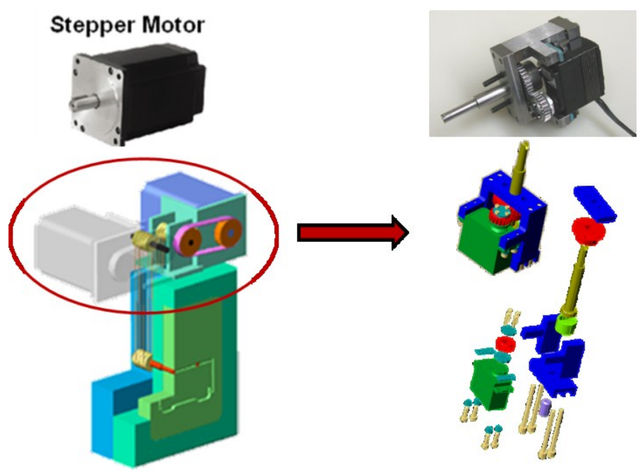


Figure 2-10: Eccentric Valve Port Configuration [29]

Through numerical simulation of the eccentric valve flow behavior, Akapot showed that by reducing the valve radius, *R*, and the offset distance, *s*, more controllable flow characteristics can be achieved. This makes the control valve more effective and optimizes the range of operating angle during the filling stage. When compared to the original valve design, the eccentric valve port has more linear response flow characteristics [29].

b. Driving mechanism

Also included in the redesign effort was the melt modulation driving mechanism. The original driving system shown in Figure 2-11 (a) was bulky, expensive and difficult to set up. The new compact driving mechanism, represented in Figure 2-11 (b), is significantly smaller, easier to use, and more cost efficient. The cost to build the original design was more than ten times that of the compact system.



(a) (b)

Figure 2-11: Original Driving Mechanism vs. Compact system [29]

c. Controller

The original controller and user interface is illustrated in Figure 2-12. All systems components were connected to a computer and controlled using LabVIEW control software.

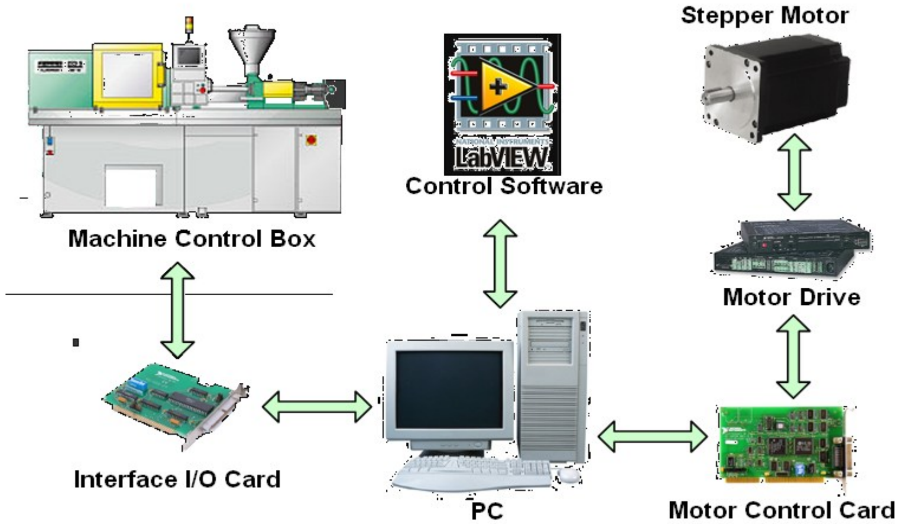
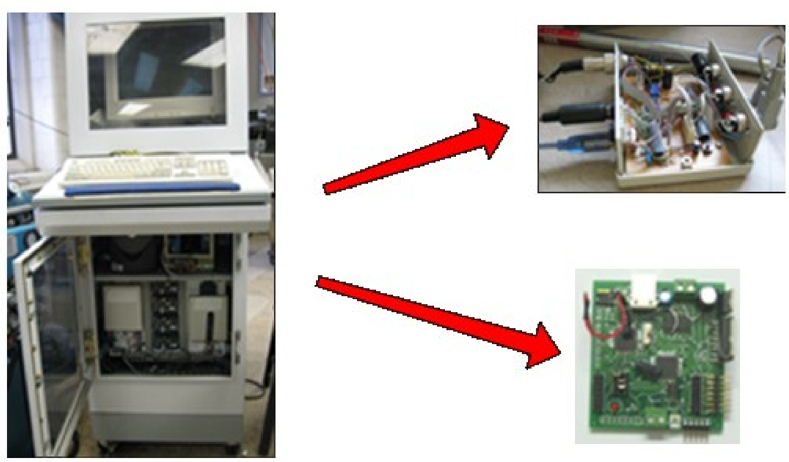


Figure 2-12: Original Controller and User Interface

Figure 2-13 (a) shows the original melt modulation controller. The compact controller, shown in Figure 2-13 (b) is about 20% of the original controller size. These improvements contributed to major cost and size reduction.



(a) **(b)**

Figure 2-13: Original Controller vs. Compact system [29]

d. **Control Techniques**

Akapot developed three different control methods for the compact melt modulation system and they are as follows:

1. **Fixed angle** method works by choosing a specific valve angle to achieve a desirable melt flow.
2. **Bang-Bang** method controls the valve by only two positions, fully-close and fully-open. The advantages of Bang-Bang method over fixed-angle method include simpler valve manipulation, better control characteristics, and less material damage from shearing.
3. **Hybrid** method is a combination of fixed-angle and Bang-Bang methods. This method eliminates the risk of having a disconnected runner due to the melt flow solidifying when Bang-Bang is causing the valve to be in a fully closed position. It also offers better control characteristics

4. **Punlop Teeraparpwong:** began setting the stage for expanding the melt modulation capabilities to control packing parameters during the packing. His major accomplishments included:

   i. Initiated the examination of the processing parameters and their impacts on optical properties

   ii. Performed numerical simulation using Moldflow to investigate the influence of the processing parameters on weight and geometric dimensional quality, including shrinkage, and deflection.

2.3.2 Limitations of Previous Development

Both ***Layser*** and ***Tantrapiwat*** demonstrated significant quality product enhancements during the filling phase of cold runner based injection molding, and added capabilities such as balanced multi-cavity molding, family molding, and weld-line position control. However, in injection molding, the packing parameters have significant impact on polymer molecular orientation as well as mechanical and optical properties of clear polymers during molding. To demonstrate the effectiveness of the melt modulation technology, controlling the melt flow and packing pressure is critical for the overall part quality. Also, the current melt modulation system is still at Technology Readiness Level 4 (TRL4) according to the NASA Technology Readiness Level Scale shown in Figure 2-14. TRL4 means the system has been validated in lab settings.

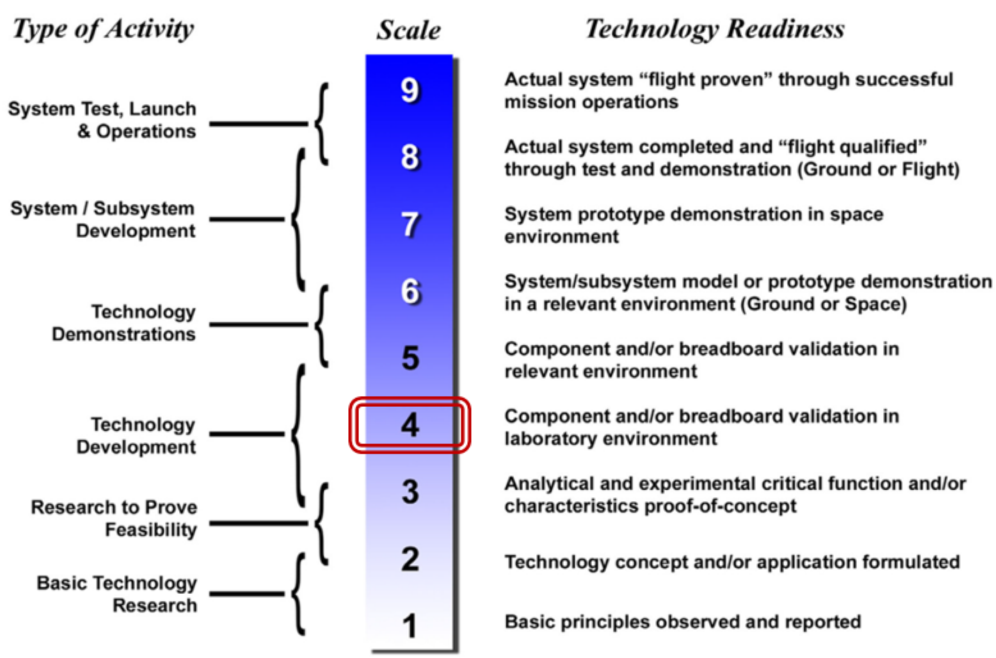


Figure 2-14: NASA Technology Readiness Level Scale [62]

In addition, the current control system still requires a computer in order to run. To improve chances of making the melt modulation system becoming "market ready" with successful launch potential, a fully integrated, a stand-alone system would be the best approach. Other system limitations include the following:

i. The application used to control melt modulation system (Delphi 7 programming code) runs only on the outdated platform of Windows XP.

ii. The control valve possesses a quick-opening characteristic for both filling & packing phases. During packing phase, any small valve rotation at certain packing times causes significant pressure drop.

iii. System control methods:

a. **Fixed Angle**: This method is supposed to provide simple procedure and can be applied with any shot size. However results from previous experiments showed the flow characteristics with a quick opening behavior which caused poor controllability.

b. **Bang-Bang**: When applying to a process which uses a small shot size and fast injection speed, it is difficult to control a valve properly. When the filling process starts, a control valve is set to be fully-closed and rotated to fully-open at a specified injection ram position. Before the control valve opens, the melt flow is stopped and can solidify. As a result, the solidified runner can prevent the cavity from being filled completely. In general, this method is sensitive to shot size and requires screw position control.

c. **Hybrid (**same as fixed-angle method): When the melt flows through a narrow channel, it suffers from high shear rate which may degrade the material and reduce the quality of the molded part. Therefore the largest possible initial fixed angle is recommended which can allow the melt flow to fill 50%-80% of the runner across that valve. This method is also sensitive to shot size and requires screw position control.

2.3.3 eGate® Electric Valve Development

While the development of melt modulation was taking place at Lehigh, Synventive developed a similar product, eGate® electric valve gate hot runner system, is for hot runner injection molding applications. The eGate® electric valve gate hot runner system incorporates a *proportional-integral-derivative* controller (*PID* controller), which is a closed feedback loop system to precisely control each valve pin's position, acceleration, velocity and stroke. The Synventive eGate was developed to meet applications that require precision and dimensional stability. It enhances product quality and improves production rate. It eliminates weld-lines (flow lines) on multi-gated parts and resolves imbalance issues and provides the ability to make family molding parts. Specific molding applications for the eGate® system include multi-shot and or multi-material applications, sequential and cascading molding and parts that require superior cosmetic surfaces. The eGate® electric valve system has many advantages over traditional valve gates and they are as follows [42]:

- Better control – it can precisely adjust the valve pin velocity and position, and thus the flow rate out of each nozzle gate at any time during the fill process

- Superior part quality – better cosmetic part/gate quality
- Process repeatability – consistency of shot-to-shot and part-to-part injection molding
- Clean, quiet and energy efficient
- Process monitoring – data gathered and monitored for real-time pin position
- Ease of service – quick start-up and high up-time

2.4 Remaining Scientific Challenges

The following are the remaining cold runner injection molding challenges:

A. Balance of melt flow filling and packing parameter of multi-cavity molds

B. Successful production of family molding parts with full process repeatability

C. Control of weld-line position

D. Packing processing parameters (pressure and time) control during an injection molding cycle.

These challenges are the motivation for my work. With these limitations in mind, I developed a modular melt modulation system to address and fulfill these unmet needs. A summary of the related scientific fundamentals is in the next chapter.

CHAPTER 3 – RELATED SCIENTIFIC FUNDAMENTALS

Injection molders are under pressure to produce high quality parts while maintaining a minimum cost. Evidently, this requires precise control of the molding process parameters to avoid residual stresses and other factors that may jeopardize the quality of the final product. One of the major factors that determine the final part quality is the polymer melt rheology.

3.1 Melt Rheology

Rheology can be defined as the study of deformation and flow of matter. The flow of polymers is more complex than Newtonian fluids such as water or air. Newtonian fluid is defined as a fluid with constant viscosity, which is the resistance to flow, at changing shear rate. A common Newtonian fluid has a viscosity that may be affected by temperature, but not by changing flow rate or shear rate. A fluid viscosity is determined by the shear stress divided by the shear rate. For most common polymers, the viscosity is Newtonian at low shear rate. However, the viscosity becomes non-Newtonian at higher shear rate during injection molding [3].

Injection molding melt flow is known to be laminar with normal Reynolds Number of ~ 10. Turbulent flow usually develops when Reynolds Number is 2300 or higher. During the filling phase of an injection molding cycle, the plastic melt exhibits a specific behavior known as “fountain flow”. Although, the fountain flow behavior develops in both hot and cold runner molds, the plastic frozen layer only does not occur in most hot runners. As the melt enters the cavity of a cold runner mold, some of the material is deposited (frozen) on the cavity walls, and the remaining hotter material flows through the frozen layer causing a flow front. The drag of the flowing melt laminates on the mold walls causing a faster flow on the center. This results in a parabolic velocity profile, or fountain flow, at the flow front as shown Figure 3-1. Typically, the material moving closer to the outer channel walls experiences some shearing. Shear rate is near zero at the mold wall and at the center of the flow channel. Maximum shear stresses are usually near the channel wall [3]. In general, the shear stress profile induces molecular orientation located in the higher shear regions in the flow direction. As these molecular orientations are frozen in, this may create an uncontrolled anisotropic molecular structure distribution, which is often associated with poor or less than optimal performance characteristics.

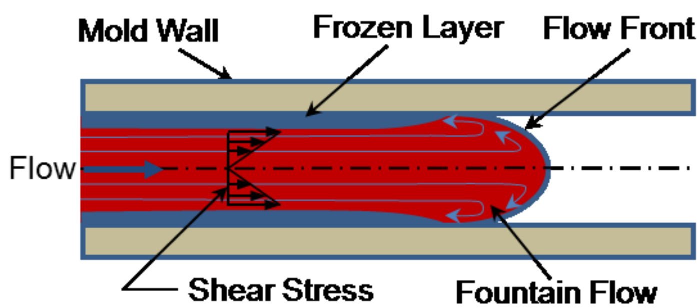


Figure 3-1: Flow Patterns and Shear Stress Profile during Mold Filling

Polymer melt rheology is usually dictated by the polymer molecular orientation, which plays an important role in shaping the final injection molded product quality. Figure 3-2 and Figure 3-3 show typical temperature and shear rate distribution across the cavity thickness respectively.

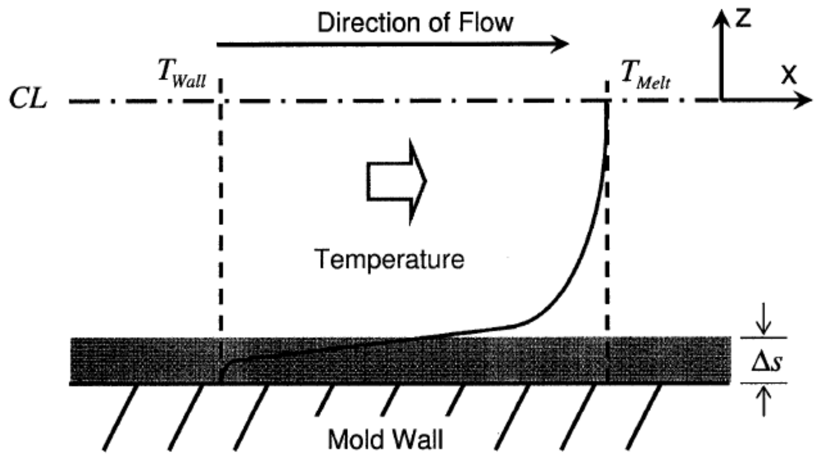


Figure 3-2: Temperature Distribution across Cavity [28]

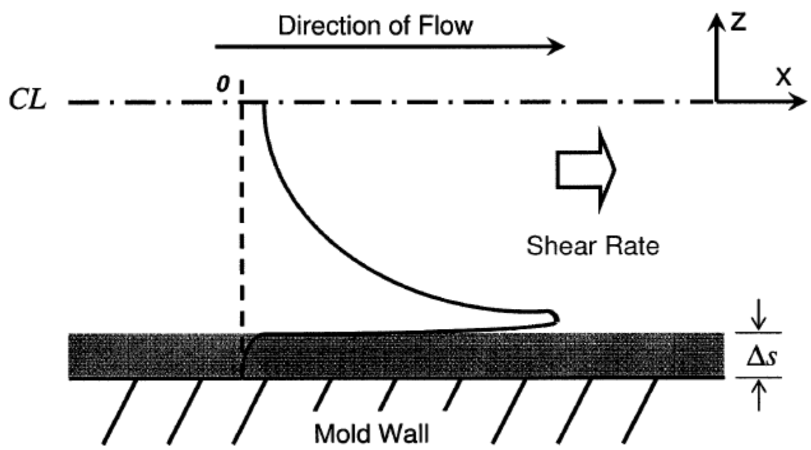


Figure 3-3: Shear Rate Distribution across Cavity [28]

Figure 3-4 shows the viscosity distribution curve, which is a result of the temperature and shear rate dependency of the viscosity. When the polymer freezes near the channel wall, thin skin layer, with a thickness (Δs), is formed during the molding process.

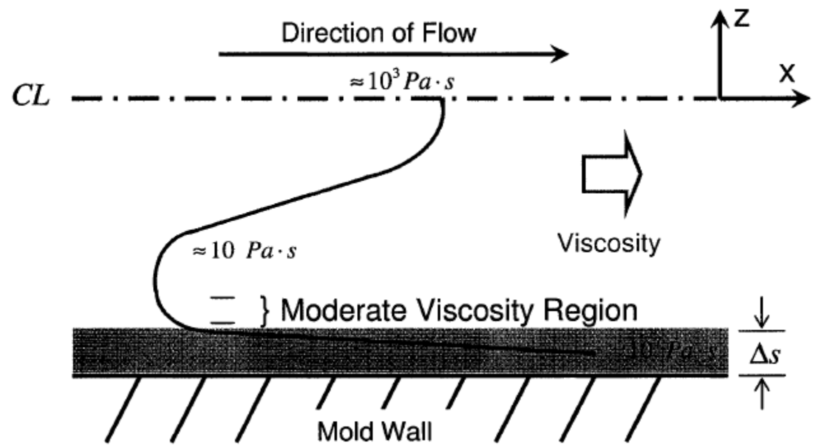


Figure 3-4: Viscosity Distribution across Cavity [28]

3.2 Control Valve Fundamentals

The flow characteristic of a control valve is defined as the relationship between control valve capacity and valve stem travel. Most valves have non-linear response - primarily due to the valve geometry. Different valve geometries affect valve capacity as the valve travels in different ways [18]. The most common characteristics for control valves are shown Figure 3-5. The valve flow percentage is plotted against valve stem position.

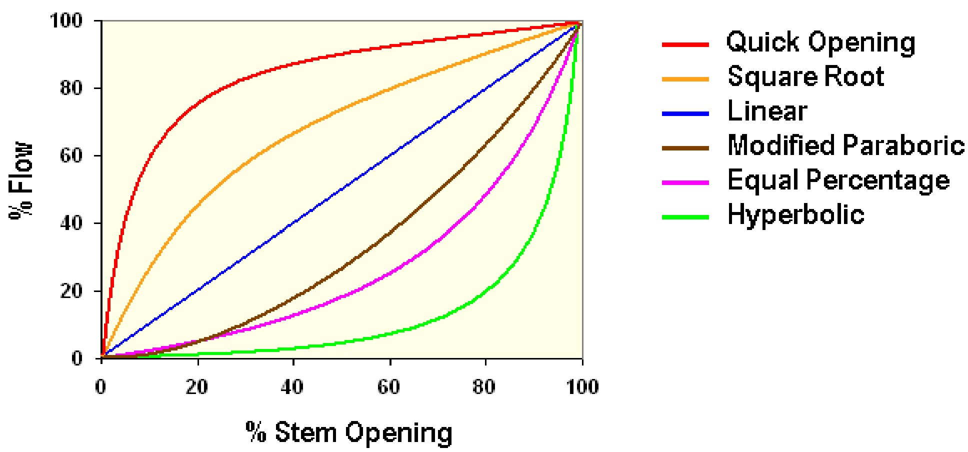


Figure 3-5: Typical Flow Characteristic Classification of Control Valves [37]

These curves are based on a constant pressure drop across the control valve. Typically, when the valve starts to open, the resistance due to fluid flow decreases the pressure drop across the valve in a non-linear fashion. Therefore, to achieve a linear curve, an equal-percentage, or modified-flow characteristics might be the best option.

The flow characteristics in a cold runner mold work the same way. The flow profile in the mold is dictated by performance of the control valve and the mold configuration. The amount of flow to the cavities depends on the control valve and valve port geometry, while the behavior of the flow is determined by the cavity and runner configurations. The relationship between the pressure drop across the control valve and the entire system is expressed as:

$$P_R = \frac{\Delta P_{valve}}{\Delta P_{system}} \tag{3-1}$$

where ΔP_{valve} and ΔP_{system} are pressure drops across the valve and the entire system respectively. A reduced pressure ratio indicates that the pressure drop at the control valve is less significant and has little impact on the entire system. As a result, the flow characteristic might resemble the quick opening behavior as shown in Figure 3-6. To compensate for this, an equal percentage valve may be used to achieve linear flow characteristic.

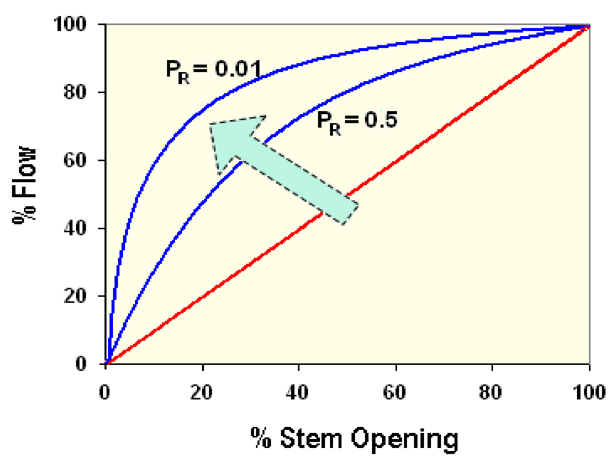


Figure 3-6: Shifting Flow Characteristic of the System According to the Pressure Ratio [29]

The relationship between the control valve and runner is illustrated in Figure 3-7. In order for the valve to be sized appropriately, the valve outer diameter must exceed the width of the runner channel. The valve port can be smaller or built with different profiles to produce desired flow control characteristics.

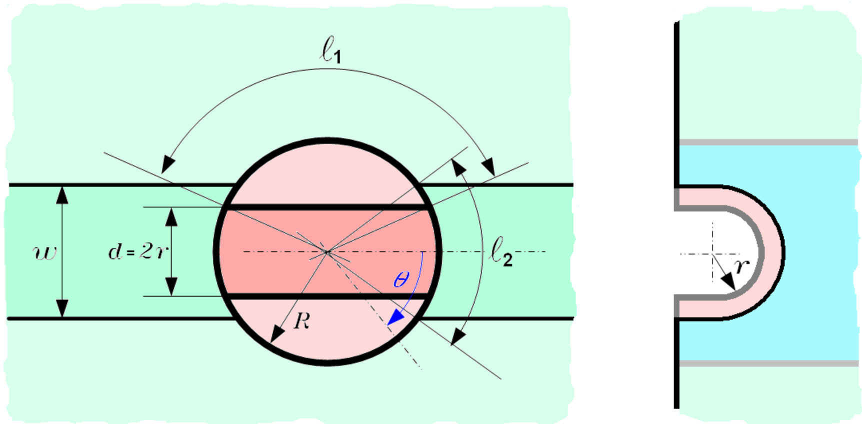


Figure 3-7: Valve Port and Runner Channel Geometry [29]

Full port is defined as the identical cross sectional area between valve port and runner channel. To improve flow control response, it is recommended to have a valve with 65% reduced cross section of the total port area [36]. To achieve a complete shut off of the valve plug when it is fully tuned, the runner channel in conjunction with the valve cord-length, l_2, should be shorter than the cord-length of valve plug, l_1.

For a runner that has a constant port width of w, the maximum width allowed at the valve port can be obtained by:

$$d \leq R\sqrt{4-\frac{w^2}{R^2}} \qquad \textbf{(3-2)}$$

where R and d are the radius and the port width of the valve respectively. Consequently, if a runner with a valve that has the same radius, R, and port width, d, the maximum controllable angle for the particular valve for a non-circular profile for both runner channel and valve port can be determined by:

$$\theta \quad = \quad \sin^{-1}\left(\frac{w}{2R}\right) + \sin^{-1}\left(\frac{d}{2R}\right) \tag{3-3}$$

Valve full port is defined as the runner width and the valve channel being equal ($w = d = 2r$). When the valve is at full port, the flow area can be obtained geometrically by projecting cross section areas on both channels. As the valve turns, the narrowest cross section at a particular turning angle θ is the overlap region between the projection areas as shown in Figure 3-8. Also, the distance, L, changes as a function of valve angle, θ, and results in a transformation on the overlapping area which can be presented by:

$$\begin{aligned} A = {} & r^2\left(2 + \cos^{-1}\left(\frac{\sqrt{(R^2 - r^2)(1 - \cos\theta)}}{\sqrt{2}\ r}\right)\right) \\ & - r\sqrt{2(R^2 - r^2)(1 - \cos\theta)} \\ & - \frac{1}{4}\sqrt{2(R^2 - r^2)(1 - \cos\theta)(4r^2 - 2(R^2 - r^2)(1 - \cos\theta))} \end{aligned} \tag{3-4}$$

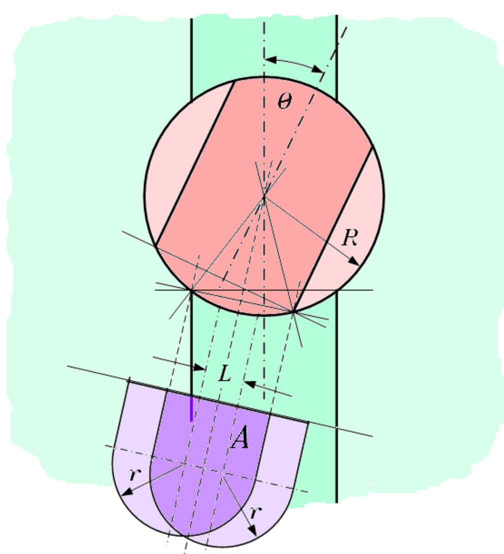


Figure 3-8: Approximate Geometry of Opening Valve Port [29]

3.3 Melt Modulation Technique

The melt modulation valve port is an eccentric rotary plug. The configuration of the eccentric valve is shown in Figure 3-9. The geometry of the eccentric valve port is similar to the design in Figure 3-7, except that it has only one plug and it is installed at a slightly offset location from the center of the runner.

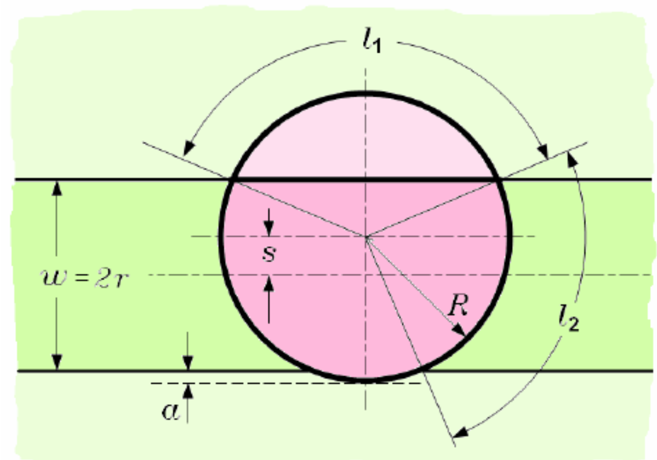
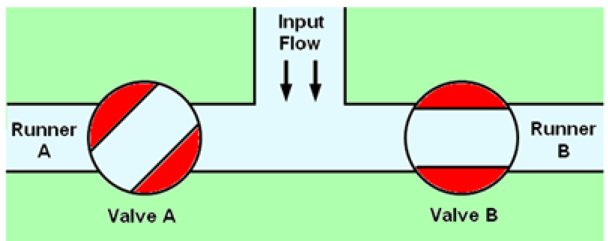


Figure 3-9: Eccentric Valve Port Configuration [29]

There is no limit on how many valves the melt modulation technology can have. However, the level of complexity in controlling the valves increases as the number of valves increases. A two-valve melt modulation system, as shown in Figure 3-10(a), has been tested to understand the flow characteristics. When the two valves (A and B) are fully open, the amount of melt flow through each valve should be the same regardless of cavity configurations. Suppose valve "A" is chosen to be the control valve while keeping valve "B" at fully open position. As valve "A" is turning toward the closing position, the flow through valve "A" decreases while it quickly increases through valve "B". Because of pressure drop across the control valve and the runner channel, the system tends to have a "quick opening" behavior as shown in Figure 3-10(b). Typically, this behavior is not desirable as it reduces the control of packing parameters during the packing phase. As a result, a suitable control valve system is critical to having an effective melt modulation system.



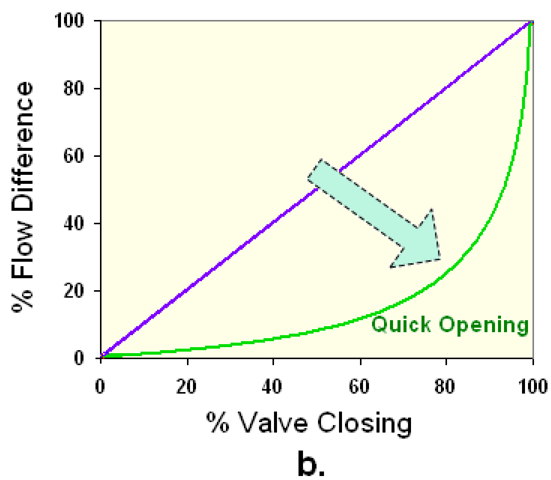


Figure 3-10: Melt Modulation System Flow Characteristics [29]

3.4 Birefringence

Transparent polymers with excellent optical properties are very useful for plastic optics applications. The most widely used polymers are Poly(methyl methacrylate) (PMMA), and Polycarbonate (PC) due to their excellent transparency. Clear polymers have many advantages such as lighter weight, lower cost, and a higher impact resistance than glass. Additionally, optical plastics have the same level of light transmittance as hi-grade glass materials. Also, when plastic breaks, the scraps are less dangerous in comparison to glass. Moreover, glass is not suitable for mass production [18].

There are two main factors that greatly affect the quality of optical plastic materials. First is birefringence in the material and the second is geometric dimension changes from the desired shape. Birefringence is an important measurement of polymer orientation. It is primarily caused by flow-induced residual stress [17] and can be seen by passing polarized light through stressed transparent material which has two refractive indexes. The refractive index, n, is defined as a ratio of the speed of light through vacuum (3×10^8 m/s), c, by the speed of light through the material, v.

$$n = \frac{c}{v} \tag{3-5}$$

Light normally moves through a transparent material in the form of waves, which are Omni-directional. When passing the light across a polarizing lens, called polarizer, only one light wave component is allowed to pass. After the polarized light passes through the transparent material, it is separated into two wave fronts which have different velocities. Each wave front is parallel to the direction of principal stress, σ_1 and σ_2. In order for birefringence to be visible, another polarizing lens called an analyzer must be placed in the path of polarized light from the material. The analyzer can be rotated to control the light intensity passing through. Eventually, the two wave fronts will cross, resulting in a noticeable color spectrum. The schematic diagram in Figure 3-11shows how to observe birefringence.

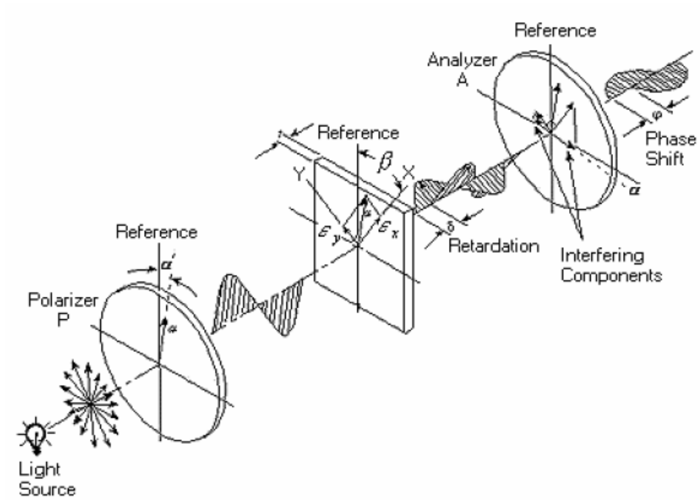


Figure 3-11: Schematic of plane polarizes scope activity [18]

Birefringence can be determined by using Brewster's Law,

$$\Delta n = n_1 - n_2 = C\left(\sigma_1 - \sigma_2\right) \tag{3-6}$$

where C is the photoelastic coefficient of a polymer. Selected values of C are listed in Table 3-1.

Table 3-1: Photoelastic Coefficient of Polymer [18]

Polymer	Photoelastic Coefficient, C (x10^{-13} cm^2/dyn)
PMMA	-6
PC	72
COP (Zeonex 480R)	6.5
PS	-55

According to equation (3-6), high molecular orientation causes a higher difference of principal stresses. Consequently, high birefringence is generated.

Since birefringence cannot be calculated directly, retardation (δ) must be determined first. Retardation is the phase difference between two wave fronts traveling through the material, which controls the intensity of the color spectrum displayed by a polarizer. The relationship between retardation and birefringence is governed by the following equation,

$$\Delta n = \frac{\delta}{t} \tag{3-7}$$

where t is the thickness of the material used to observe birefringence. Retardation can be calculated by the relationship between the wavelength (λ) and the fringe order (m), which can be manually counted through a polarizer.

$$\delta = m\lambda \tag{3-8}$$

The two main causes of birefringence during injection molding process are flow-induced and thermally-induced residual stress.

Geometric dimension tolerance is another crucial factor that defines optical quality. Major dimensional problems that could occur in injection molded optics are shrinkage, warpage, and surface quality. The shape quality of molded optics primarily depends on the processing parameters of the injection molding process, including melt temperature, mold temperature, packing pressure, and packing time.

CHAPTER 4 – DEVELOPMENT OF MODULAR MELT MODULATION SYSTEM

4.1 Introduction

Successful product development starts with solving the right problem. Understanding the need that must be fulfilled or the problem that needs to be addressed coupled with knowledge of basic science principles, such as rheology of plastics, filling and packing effects of molded thermoplastic materials and basic operations of cold runner injection molding, is essential in developing a melt flow control system. The design and development of the modular melt modulation system began with understanding the market needs and customer requirements. This chapter focuses on the development of the modular melt modulation systems.

Two previously designed melt modulation systems were developed; the original and the compact melt modulation systems. Both former systems were analyzed thoroughly to learn their capabilities and the limitations. The melt modulation design was implemented on a standard two-plate mold with a nominal size of 8 x 10 similar to the one shown in Figure 4-1.

Figure 4-1: Two Plate Mold Base Configuration (Source: DME electronic catalog)

All the mold plates are stacked together and mounted inside the mold chamber of the injection molding machine. There are several different sizes and configurations of injection molding machines. They are usually categorized by their clamping force and injection rate as well as their processing method and configuration (i.e. hot vs. cold runner and horizontal vs. vertical injection molding machines).

A 3-D model of a standard injection molding machine is shown in Figure 4-2. For safety reasons, the mold assembly has to be contained within the mold chamber and the sliding doors must be completely closed in order for the machine to run. There is a small opening underneath the mold assembly in the mold chamber. This opening allows for the ejected parts to be dropped in a collection basket or container. There is also another small opening directly above the mold assembly, but in general, the available space around the mold assembly is very limited and may not accommodate additional apparatus.

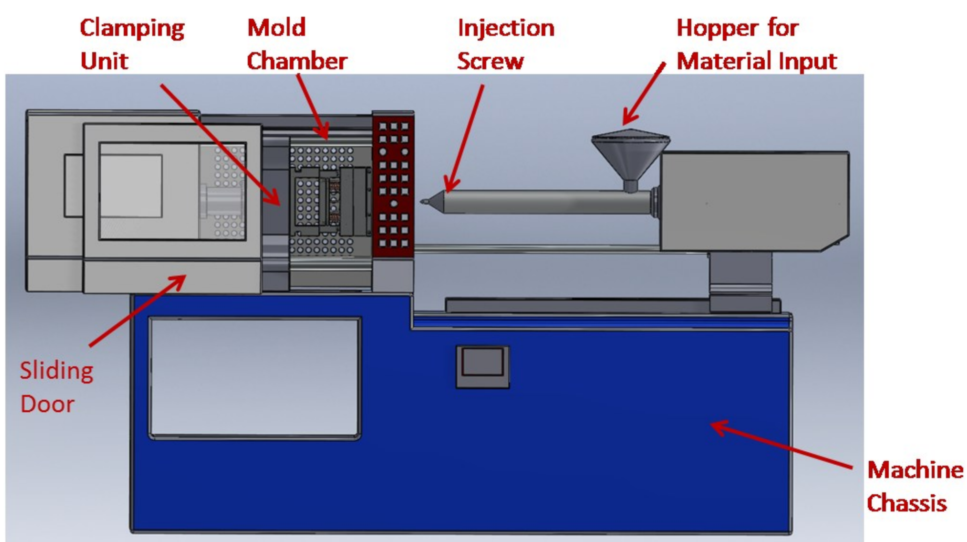


Figure 4-2: 3-D Model of a Standard 40-ton Nissei Injection Molding Machine

The original melt modulation system had many disadvantages that made it impractical to implement. Figure 4-3 shows the supporting equipment required in order to operate the original system, some of which can be expensive. Also, it had to be mounted on the mold directly as illustrated in Figure 4-4. Other limitations of the original designs include the following:

1. Large size and space requirement
2. Entailed many modifications to the mold base
3. Required many components, which increased costs significantly
4. High tooling cost

As a result, this created a need for an improved and more practical design.

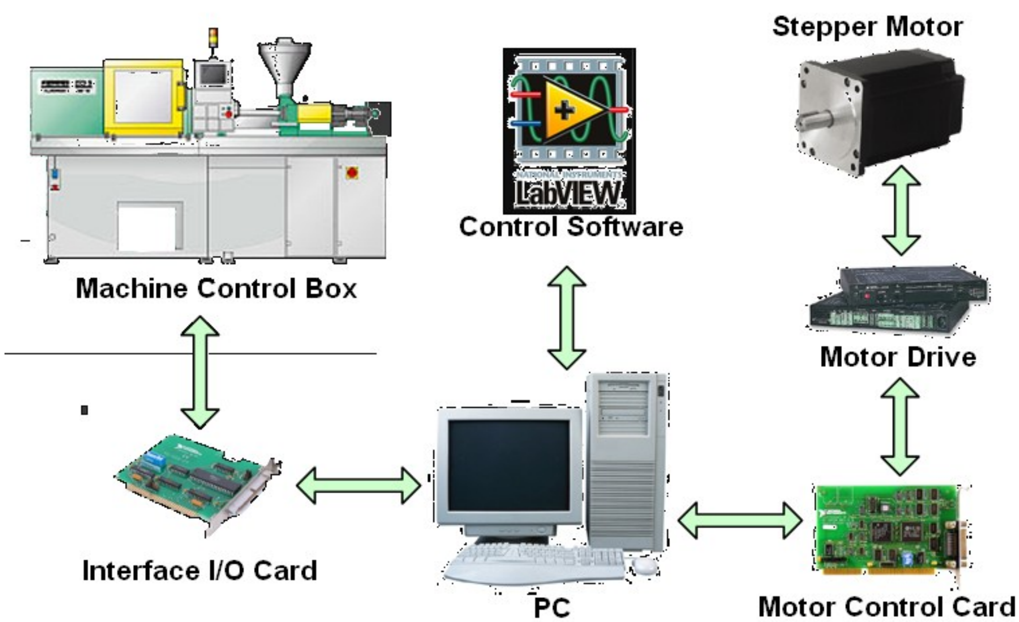


Figure 4-3: Original Melt Modulation System Supporting Equipment

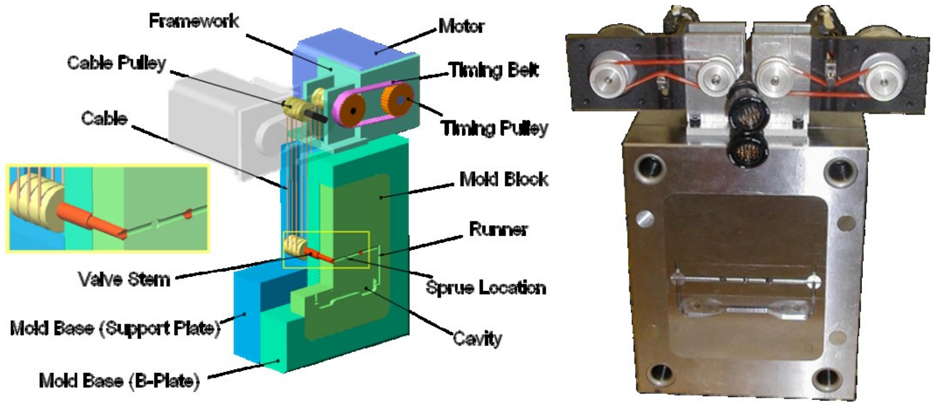


Figure 4-4: Original Melt Modulation System (left: 3-D Model, right: Actual Picture)

The original melt modulation design had undergone many design improvements over the years. The last one was the compact melt modulation system and can be seen in Figure 4-5 and Figure 4-6. Chapter 2 contains more details about both the original and the compact melt modulation systems.

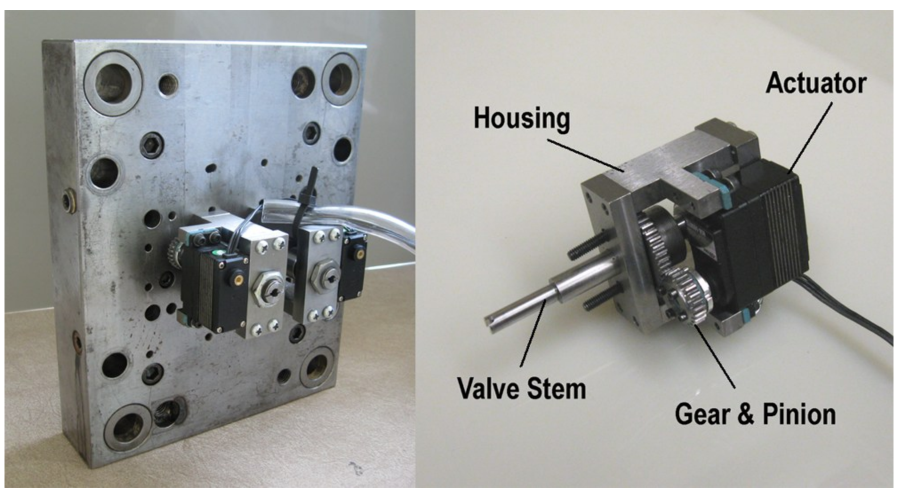


Figure 4-5: Compact Melt Modulation Valve Driving Mechanism (Prototype)

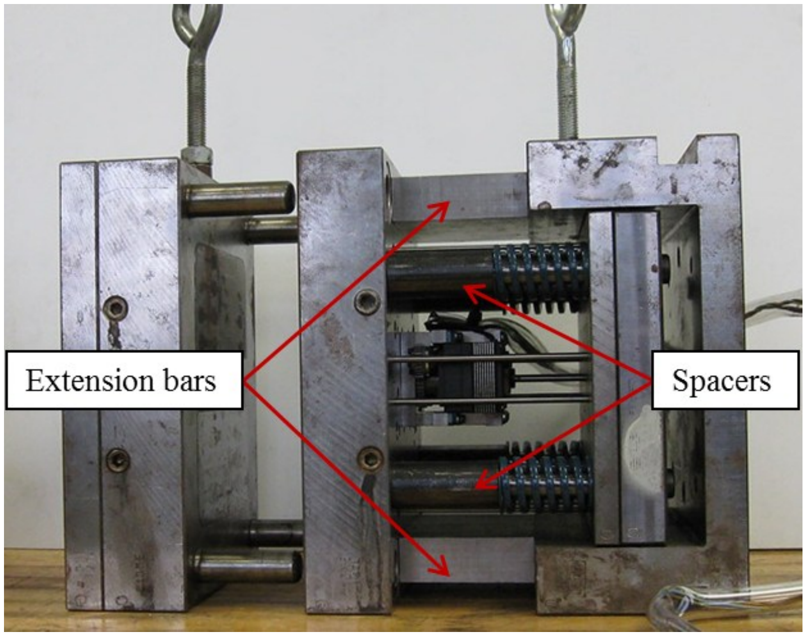


Figure 4-6: Compact Melt Modulation Mold Base with Control Valve Driving Mechanism

4.2 Design of the Modular Melt Modulation System

The basic principle of the melt modulation concept is: using rotary valves to control melt flow and packing pressure of polymers in a way that defines the final quality of the injection molding part. Prior to developing the modular melt modulation system, I derived the following technical specifications:

1. Modular design to allow for future expansion
2. Easy installation and setup
3. Fully integrated stand-alone system with user interface touch screen LCD. No personal computer (PC) is required
4. Electric (AC powered) as primary source, but can be battery operated
5. Low power consumption
6. Low voltage demand (7-12 Volts)

7. Simple control system (open loop control system)

8. Precise valve control for both filling and packing stages

9. Multi control modes (manual and automatic)

10. Easy to use, simplified user interface.

11. Valves are embedded in the mold assembly

12. Relatively small in size, 7.5” long by 7.5” wide by 7” deep.

13. Low ownership cost (1/10 of original system)

14. Safe to operate

15. High quality system

16. Excellent process repeatability

17. Clean, quiet and energy efficient

18. Process monitoring – data gathered and monitored for real-time valve position

19. Quick start-up time

20. Technology Readiness Level 6 (TRL6)

The new modular melt modulation system I have designed and developed meet these specifications. The development of the modular system has been completed to be at Technology Readiness Level 6 (TRL6) according to the NASA Technology Readiness Level Scale shown in Figure 4-7. TRL6 means the system is in a prototype stage where it can be tested in an industrial setting.

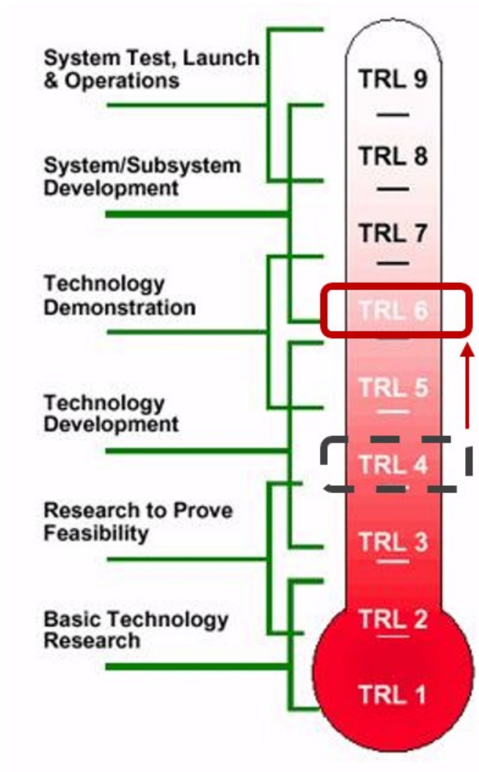


Figure 4-7: NASA Technology Readiness Level Scale [63]

The new modular melt modulation system consists of three major units:

1. Control Valves and Driving Mechanism
2. Modular Mold Assembly
3. User Interface Control (UIC)

The control valves driving mechanism is the actuation system which includes the actuators and the gearbox. The actuators directly and precisely control the valves based on inputs received from the user interface control unit (UIC). The modular mold assembly contains a standard mold base and the modular cavity inserts. Finally, the user interface control (UIC) unit has a microcontroller and a servo controller that sends the command signals to the actuators, enabling them to perform certain tasks based on the selected control scheme. All three units are detailed below.

4.2.1 Control Valves and Driving Mechanism

The new melt modulation system has control valves embedded into the mold assembly. This provides a modular and economical configuration, easy setup, and zero maintenance requirements. The control valves are driven directly by high-torque servo motors, ensuring high performance and precise control valve positioning. The current prototype design has four 1/4" diameter valves and four servo motors as shown in Figure 4-8.

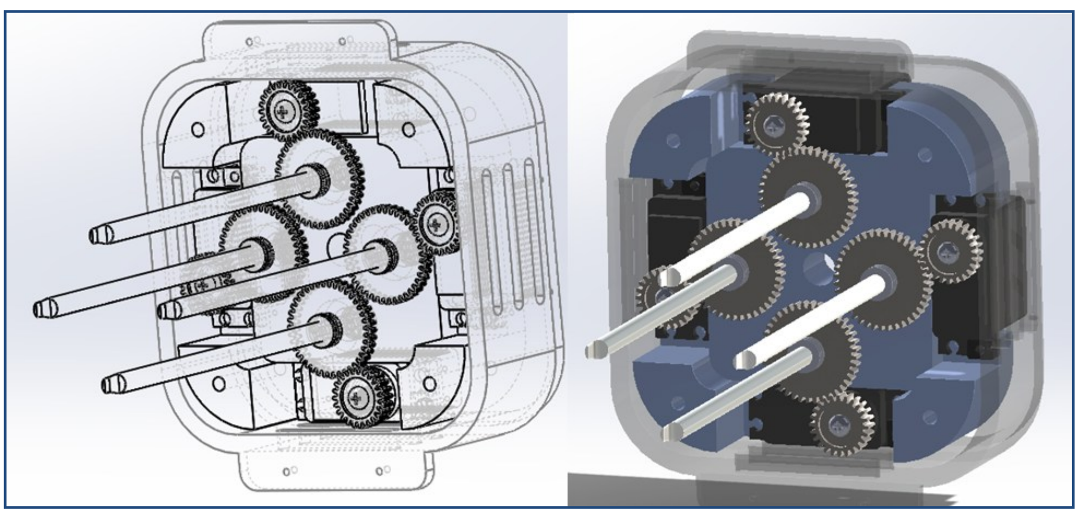


Figure 4-8: Driving Mechanism

4.2.1.1 Control Valves

The original melt modulation system had rotary valves, each containing an internal stem for the purpose of ejecting the completed part. The configuration of the original valve port is shown in Figure 4-9(a). When the performance of the original control valve was tested, the results showed that this valve port configuration caused undesired quick opening characteristics [29]. As a result, the valve design was simplified to just a stem, which is illustrated in Figure 4-9(b). The simplified valve is eccentric and can control the melt flow and act as an ejector pin at the same time.

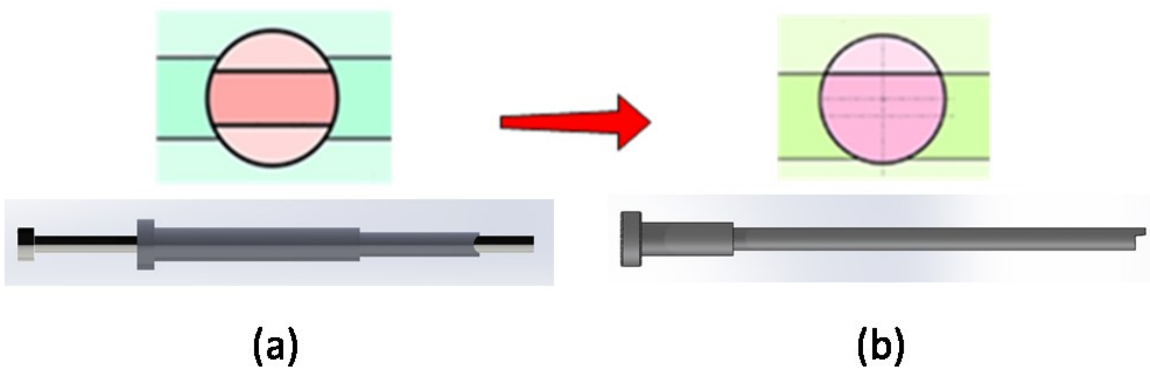


Figure 4-9: Control Valve, (a) Original Valve with a Stem, (b) Compact System

To further simplify the valve, improve the control valve performance while reducing the cost of valve, the current modular design incorporates a standard "off the shelf" ejector pin with a modified port that matches any round or parabolic runner configuration with a matching draft angle. An example of a parabolic valve with a draft angle of 5^{o} is shown in Figure 4-10. The draft angle can be changed to match the runner profile to eliminate any unnecessary melt flow shear or restrictions.

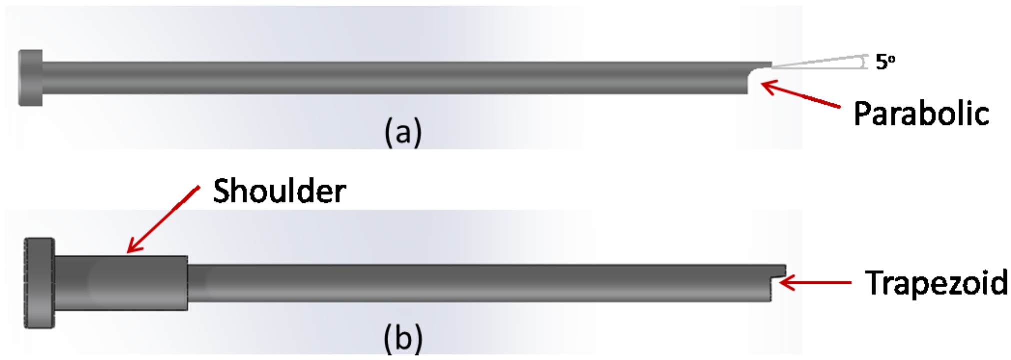


Figure 4-10: Control Valve, (a) Modular System, (b) Compact System

A 3-D cross-section view of the modular melt modulation control valve in the runner is shown in Figure 4-11.

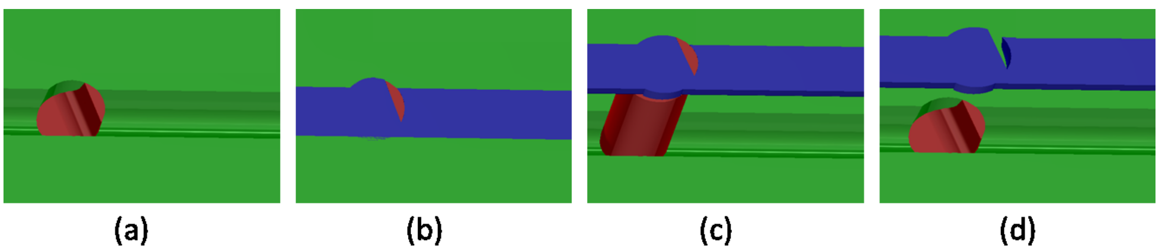


Figure 4-11: A 3-D Cross-section View of the Modular Melt Modulation Control Valve:

(a) Pre-Filling (b) During Filling (c) Ejecting (d) Part Removal

The modular melt modulation valve port is also an eccentric rotary plug. The configuration of the eccentric valve is shown in Figure 4-12. The geometry of the eccentric valve port is similar to the design in Figure 3-7, except that it has only a pin and it is installed at a slightly offset location from the center of the runner.

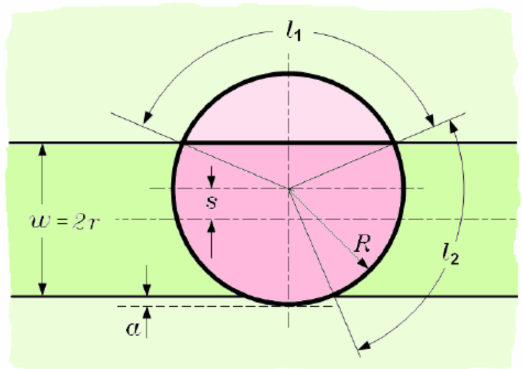


Figure 4-12: Eccentric Valve Port Configuration [29]

The operating angle of the eccentric valve port design can be determined as:

$$\theta \quad = \quad \sin^{-1}\left(\frac{r-s}{R}\right)+\sin^{-1}\left(\frac{r+s}{R}\right) \qquad \textbf{(4-1)}$$

where r is half of the cold runner width, R is the valve port radius, and s is the offset distance from the center of valve and the center of the runner. For proper operation of the valve from fully open to fully closed position, the design parameters have to be selected so that the cord-length of valve plug, l_1, is longer than the runner channel in conjunction with the valve cord-length, l_2, as in Equation (4-2):

$$l_1 \; = \; R\theta \qquad \geq \quad l_2 = 2\,R\cos^{-1}\left(\frac{r-s}{R}\right) \qquad \textbf{(4-2)}$$

A numerical simulation study of the eccentric valve flow behavior showed that by reducing the valve radius, R, and the offset distance, s, in equation (4-1), more controllable and flow characteristics can be attained [29]. This makes the control valve more effective and optimizes the range of operating angle during the filling stage. When compared to the valve design in Figure 3-7, the eccentric valve port has more linear response flow characteristics and provides more effective flow and packing control.

To ensure the eccentric valve seals the runner at closed position during the packing phase, the seating distance, α, should be greater than zero as follows:

$$\alpha = R - r - s \quad > \quad 0 \tag{4-3}$$

The melt modulation valve diameter has been selected to be 1/4" in diameter, while the offset distance was selected to be 0.02" according to the prototype designed. Table 4-1 presents all parameters of the eccentric valve port used for the packing stage control application.

Table 4-1: Eccentric Valve Port Parameters

Parameter [units]	**Value**
Valve Radius, R [in]	0.1250
Half of Runner Width, r [in]	0.0938
Offset Distance, s [in]	0.0200
Range of Operating Angle, θ, [degree]	67.79
Curvature l_1 [in]	0.2930
Curvature l_2 [in]	0.1490
Valve Seating Distance, α [in]	0.0113

In order to ensure good valve performance, some of the control valve parameters in Table 4-1 were carefully selected. For example, to ensure the valve completely shuts off the flow and seals the runner properly when it is fully closed, the seating distance, α, has to be greater than zero. Other parameters were selected based on sizes of widely available tooling. According to runner design standard, it is recommended that the runner is shaped as a full round or parabolic and its diameter to be at least 1.5 times the thickness of the cavity [3]. Since the maximum thickness of the cavities used was approximately 1/8” thick, the runner was chosen to be parabolic with a diameter of 3/16”.

In addition, when the parameters used in Table 4-1 were utilized with a similar valve configuration, the results showed better flow control and performance [29]. The result can be seen in Figure 4-13, where the compact system valve (labeled ‘new valve’ on this graph) produced more of a linear control response.

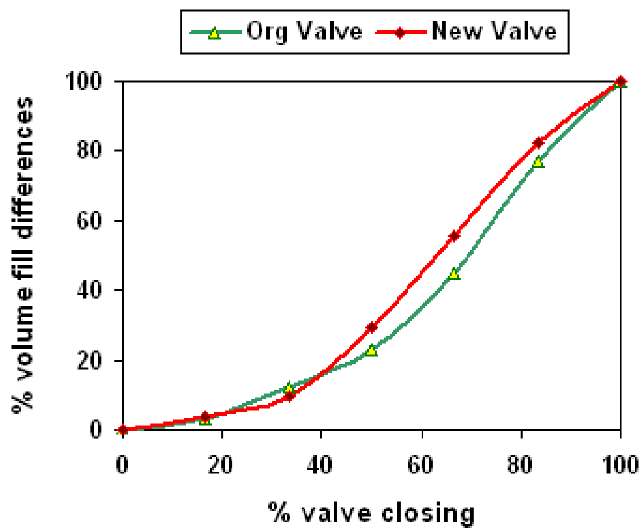


Figure 4-13: Flow Characteristics, Original Valve vs. Compact System (New Valve) [29]

Another aspect of ensuring a good valve performance is determining the valve closing direction. Figure 4-14 (a) and (b) show the two different methods of closing the control valves. Both methods were investigated and it was determined that the valve produced better flow characteristics when closed prior to the melt entering the valve, Figure 4-14 (b). In addition, the control valve encountered less resistance and, therefore;

required less torque to close [29]. As a result, the closing action shown in Figure 4-14 (b) has been selected.

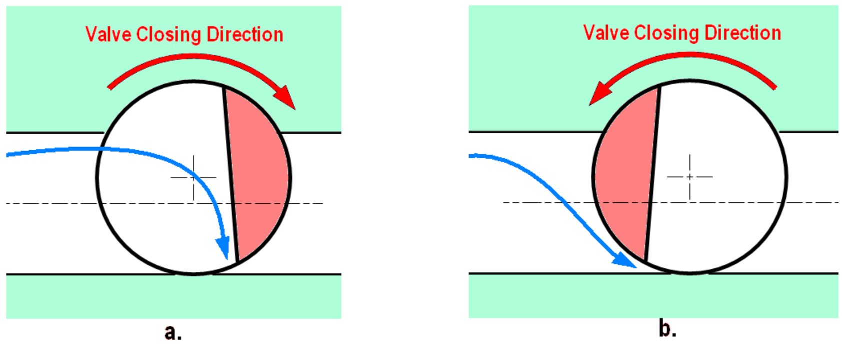


Figure 4-14 Control Valve Closing Direction [29]

Additional control valves can be incorporated to the modular melt modulation system as long as there is enough physical space on the mold base. The number of control valves is usually determined by the number of runners used. Ideally, it is a ratio of 1:1. If, for example, the modular melt modulation system is implemented where the number of runners exceed the number of control valves used, the system will only control flow and packing pressure through runners with valves. Also, as the number of control valves increases, the level of complexity in controlling the melt increases as well because the melt flow is nonlinear.

4.2.1.2 **Actuator**

An actuator is a device that converts energy (i.e. electrical, pneumatic, etc.) into a physical motion. The vast majority of actuators can either produce linear or rotational motion. Choosing the right actuator requires an understanding of the system requirements and is critical to achieving a high performance design. Based on the design specifications, actuators that can transform electrical energy to rotational motion were required.

There are two mechanical characteristics that differentiate electrical actuators; torque and rotational speed. Since this is an industrial application where very high torque is required, it is more efficient and convenient to have AC (alternating current) source to power the actuators, or where the motors are powered by a power supply source that is connected to the wall outlet.

Since the control valves are required to rotate in both clock-wise (CW) and counter clock-wise (CCW) directions, high torque rotary actuators (servo motors) were selected for the valve driving mechanism.

In order to determine the proper size actuator required to operate the control valves, the torque requirements had to be established. In previous development, simple torque measurements of the valve stems turning with a range of packing pressures that were applied to the system were conducted [29]. Figure 4-15 shows the range of torque required to turn the control valves at different levels of packing pressure. The measurement included turning the valve from open to closed and closed to open as well as using a dummy valve, which is just a valve stem without a port. Depending on the direction of turning the control valves, the torque requirements were slightly different.

However, in the case of the dummy valve, the torque requirement stayed relatively the same even under high packing pressure.

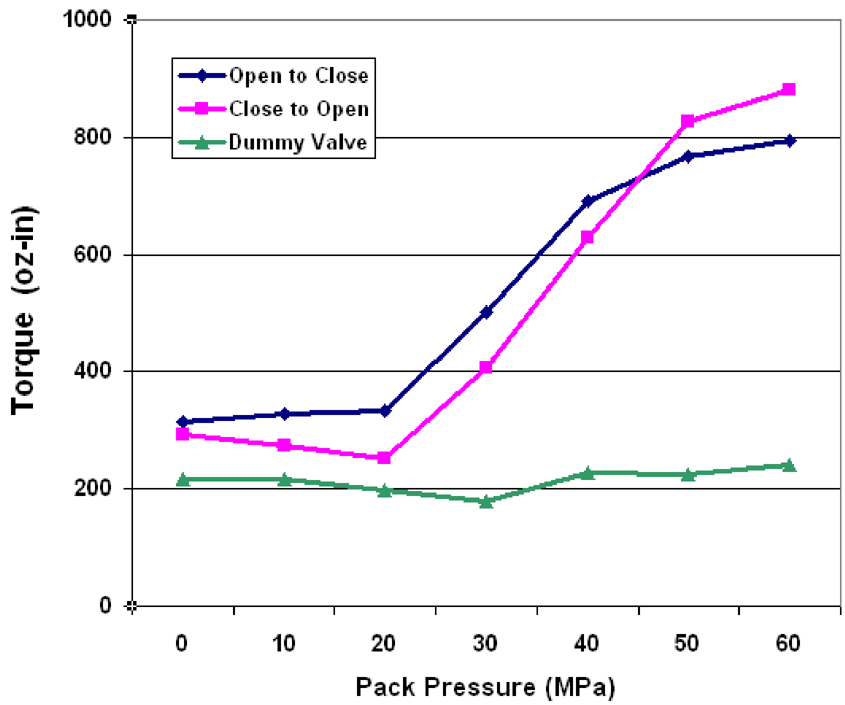


Figure 4-15: Measured Torque for Turning Control Valve at Different Packing Pressure [29]

As it is unlikely for the melt modulation system to be applied with a maximum packing pressure, it was estimated that it would withstand 80% of the maximum packing pressure. Based on this assumption, the control valves require a driving mechanism that must overcome approximately 700 oz-in of torque. Based on the torque measurements, the torque required to turn the valve at zero packing pressure was slightly over 300 oz-in, which is very high. For that reason, the original system had large actuators outside the mold assembly. However, the new system must have small, embedded and less costly actuators. One way to overcome this high torque requirement is to select a high efficiency gear train to overcome the initial torque required at zero packing pressure (300 oz-in).

This will reduce the overall torque requirement on the actuator to 400 oz-in. As a result, the gear reduction was reduced to a single transmission step.

The transmission system used on the original melt modulation design was a set of wire cables and pulleys that transmitted rotation from outside the mold. Another set of timing pulleys were also employed to transmit power from the actuator to the mechanism. However, this configuration was not efficient due to the high friction caused by cables and pulleys. To reduce friction and improve transmission efficiency, an embedded gear train design would be more suitable, especially since the mold base has a limited space. Given the desired location to mount the driving mechanism and the geometry of the actuators and the control valves, a set of four spur gears were selected. Furthermore, spur gears have high efficiency and small backlash. The modular melt modulation driving mechanism can be seen in Figure 4-16.

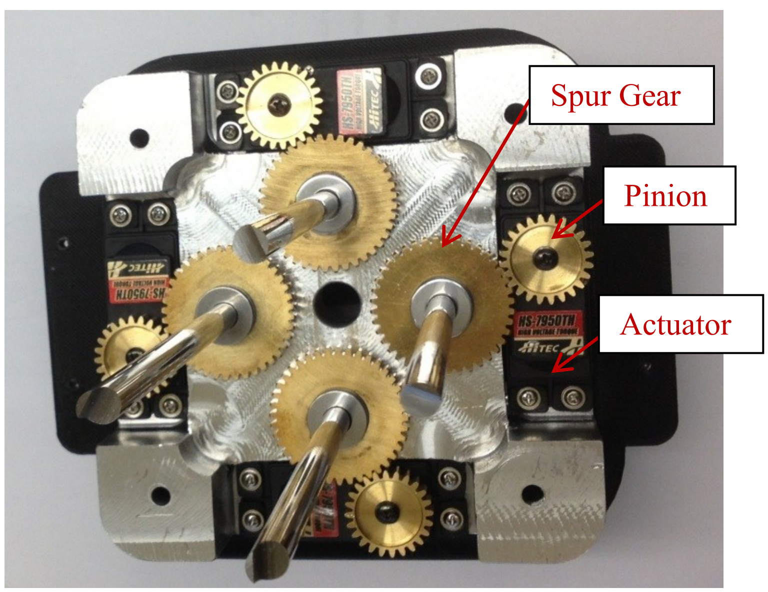


Figure 4-16 Driving Mechanism for Modular Melt Modulation Prototype

Figure 4-17 shows a 24 tooth pinion gear driving a 40 tooth spur gear. The gear module and number of teeth were selected based on the output torque and rotational speed requirement. To determine the drive gear revolutions needed to turn the driven gear one complete revolution, the gear ratio must be calculated. The gear ratio (***GR***) can be calculated as follows:

$$GR = \frac{N_B}{N_A} \tag{4-4}$$

where $\boldsymbol{N_A}$ and $\boldsymbol{N_B}$ represent the number of drive gear (pinion) teeth and the number of driven gear teeth respectively. According to equation (4-4), each spur gear provides a torque ratio of 1.667:1 (or 40:24).

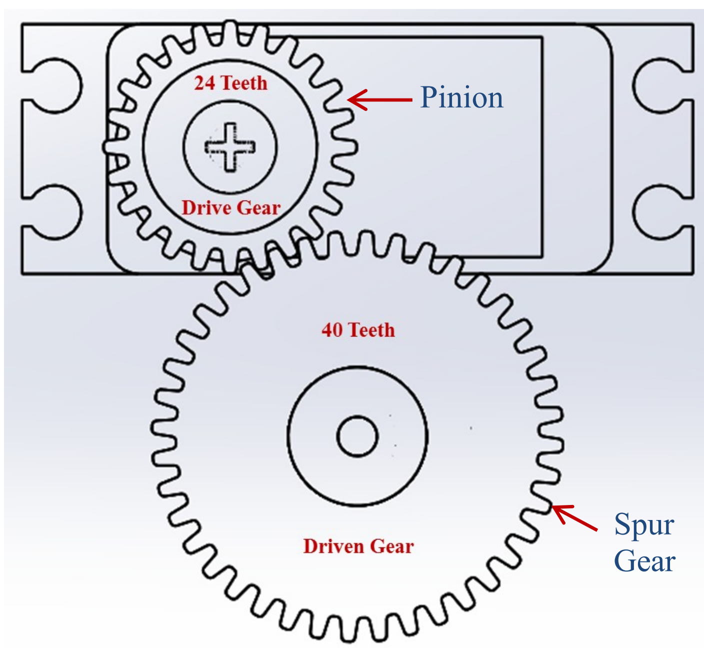


Figure 4-17: "Low" Gearing to Increase Torque

The gears used in the gear train had the same pitch number of 32. To ensure robust gear system efficiency, the gear train power transmitting efficiency can be estimated by:

$$E = 100 - P \qquad \textbf{(4-5)}$$

where P is the percentage of power loss of the gear train and can be calculated by:

$$P = \frac{50\mu}{\cos\alpha}\left(\frac{H_s^2 + H_p^2}{H_s + H_p}\right) \qquad \textbf{(4-6)}$$

where,

$$H_s = (GR+1)\left[\left(\sqrt{\left(\frac{OD_s}{PD_s}\right)^2 - \cos^2\alpha}\right) - \sin\alpha\right] \qquad \text{and} \qquad \textbf{(4-7)}$$

and

$$H_p = \left(\frac{GR+1}{GR}\right)\left[\left(\sqrt{\left(\frac{OD_p}{PD_p}\right)^2 - \cos^2\alpha}\right) - \sin\alpha\right] \qquad \textbf{(4-8)}$$

Where, $\boldsymbol{\mu}$ is the coefficient of friction, $\boldsymbol{\alpha}$ is the gear pressure angle, $\boldsymbol{OD_s}$ and $\boldsymbol{OD_p}$ are the outside diameter of the spur gear and the pinion, $\boldsymbol{PD_s}$ and $\boldsymbol{PD_p}$ are pitch diameter of the spur gear and the pinion respectively. The details of the gear parameters are summarized in Table 4-2.

Table 4-2: Gear Train Specifications

Specifications	Gear	Pinion
Pitch Number (N_p)	32	32
Number of teeth (N)	40	24
Pitch Diameter (***PD***)	1.25 inch	.75 inch
Outside Diameter (***OD***)	1.30 inch	0.8 inch
Pressure Angle (α)	20 degree	20 degree

Since the driving mechanism has thrust bearings, there is very little friction. However, if we assume the control valve coefficient of friction is approximately 0.65, the total gear efficiency drops to 95 %. This leads to a maximum torque of 665 oz-in required to turn the control valve, which is adequate for the power requirement that has been previously established.

The modular melt modulation system requires a powerful actuator with precise speed and position control. Based on these requirements, digital servo motors with optical encoders were selected. Basically, a servo is a small device that incorporates a two wire DC motor with an output shaft, a gear train, a potentiometer, and an integrated circuit. A servo comes with three wires: one is for power, one is for ground, and one is a control input line. The signal from the control line determines the angular position of the servo shaft. The angular position of the shaft will remain in position as long as the coded signal exists on the control input line. If the coded signal changes, then the angular position of the shaft changes accordingly. Also, a servomotor was selected because it has the ability to deliver high torque in comparison to other types of motors. Typically, digital servomotors have instant response as they are designed for precise control applications. Their fast motion response is attributed to their digital microprocessors, which are ten times faster than an analog servo. Moreover, digital servomotors have three times the standing torque of an analog counterpart. Servomotors are usually available with different power requirements and turning configurations. Because it is safer to handle low voltage, DC servo motors were selected. Based on these criteria, a second generation high performance Hitec "Ultra Torque" HS-7950TH digital servomotor, shown in Figure 4-18, was selected. This servo has a programmable digital circuit, Titanium gear set, heatsink case, and ultra-power coreless motor.

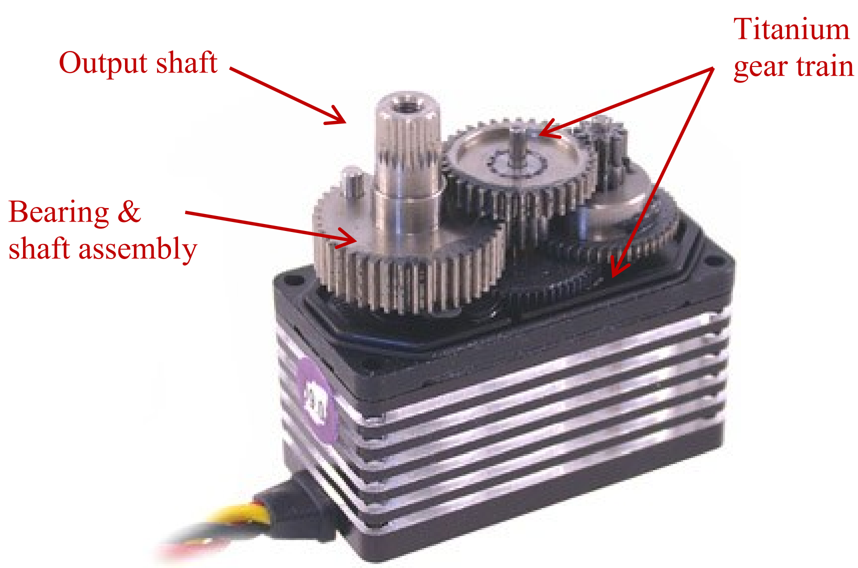


Figure 4-18: Titanium Gears, Hitec HS-7950TH Servomotor [49]

Compared with the first generation Hitec servos, this new servo has wear resistant titanium gears (inside the servo housing) with two hardened steel gear pins and axial brass bushings mounted in the service case as well as a circuit that has twice the resolution with added programmable overload protection. The HS-7950TH has a 90° rotation in both clock-wise (CW) and counter clock-wise (CCW) directions. It also has a torque of 486 oz-in at 7.4 volts, which exceeds the torque requirement of 400 oz-in to turn the control valves. The actuator specifications details are presented in Table 4-3.

Table 4-3: Hitec HS-7950TH Servomotor Specifications

Modular Melt Modulation Actuator Specifications	
Control System	+Pulse Width Control 1500usec Neutral
Required Pulse	3-5 Volt Peak to Peak Square Wave
Operating Voltage Range	4.8-7.4 Volts
Operating Temperature Range	-20 to +60 Degree C (-4F to +140F)
Operating Speed (4.8V)	0.18 sec/60° at no load
Operating Speed (6.0V)	0.15 sec/60° at no load
Operating Speed (7.4V)	0.13 sec/60° at no load
Stall Torque (4.8V)	344oz/in. (22kg.cm)
Stall Torque (6.0V)	402oz/in. (29kg.cm)
Stall Torque (7.4V)	486oz/in. (35kg.cm)
Operating Angle	45 Deg. one side pulse traveling 400usec
Continuous Rotation Modifiable	Yes
Direction	Clockwise/Pulse Traveling 1500 to 1900usec
Idle Current Drain (4.8V)	9mA at stop
Idle Current Drain (6.0V)	9mA at stop
Current Drain (4.8V)	220mA/idle and 3.8 amps at lock/stall
Current Drain (6.0V)	300mA/idle and 4.8 amps at lock/stall
Dead Band Width	1usec
Motor Type	Coreless Carbon Brush
Potentiometer Drive	6 Slider Indirect Drive
Bearing Type	Dual Ball Bearing MR106
Gear Type	Titanium Gears
Connector Wire Length	11.81" (300mm)
Dimensions	1.57" x 0.79"x 1.50" (40 x 20 x 38mm)
Weight	2.40oz (68g)

4.2.2 Modular Mold Design

The modular mold design encompasses a standard mold base and modular cavity inserts for quick and easy attach and detach. Typically, mold assemblies have a single cavity insert. The insert may have multiple cavities, but they are all on a single insert. If any single cavity has to be removed, the entire mold assembly must be completely removed from the injection molding machine and taken apart to remove the insert. This process can take two hours or more, depending on the complexity of the mold base. Set-up time could be reduced if every cavity insert had its own mold assembly, but that would costly. To reduce material costs and set-up time, modular cavity inserts have been developed. The idea started with a design of a modular cavity insert assembly, with cavity inserts that connect to each other just like a puzzle, as shown in Figure 4-19.

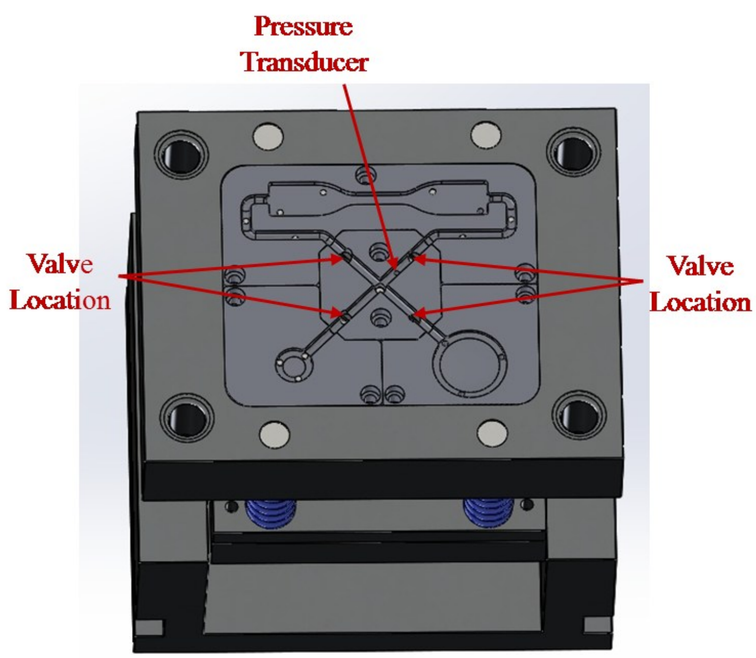


Figure 4-19: Modular Mold Assembly (4-Valve configuration)

All modular cavity inserts are mounted to a base plate and the entire assembly is mounted on the B-plate. This allows every cavity insert to be individually removed or replaced easily and quickly. This insert/change can be done by leaving the valve insert and the base plate mounted to the B-plate and the mold assembly. The entire cavity insert/change process can be completed in less than one minute. Figure 4-20 shows an exploded view of the modular cavity inserts assembly. This design not only saves money and time, but it provides the ability to make different assemblies in one injection molding cycle.

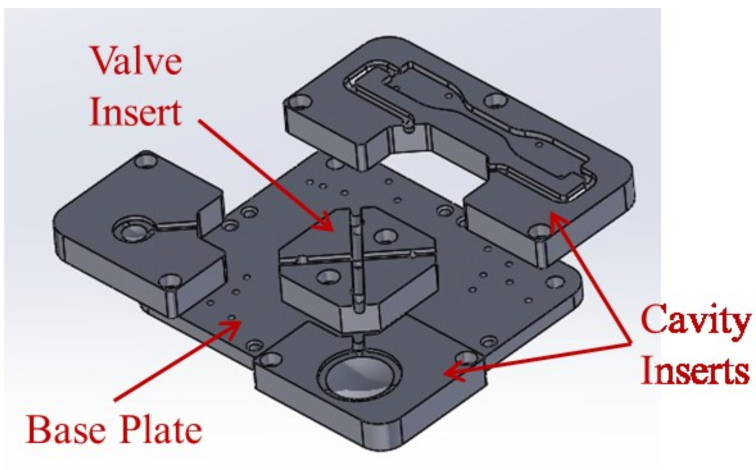


Figure 4-20: Modular Cavity Inserts Assembly – Exploded View

The modular cavity inserts assembly can be configured in many different ways, as illustrated in Figure 4-21. In matter of minutes or even seconds, the mold assembly can be configured to control weld-line position, multi-cavities, and/or family molding. Figure 4-21(a) shows an example of two identical cavities, each with two runners for weld-line position control. When the two cavities are dissimilar, this configuration will allow for both weld-line position and multi-cavity control. If three cavities are required for a specific application, the configuration in in Figure 4-21(b) can be used. If all three cavities have single runners, then the forth valve can be shut off. Finally, if the application requires four duplicate cavities or just an assembly of four different parts, then Figure 4-21(c) can be used.

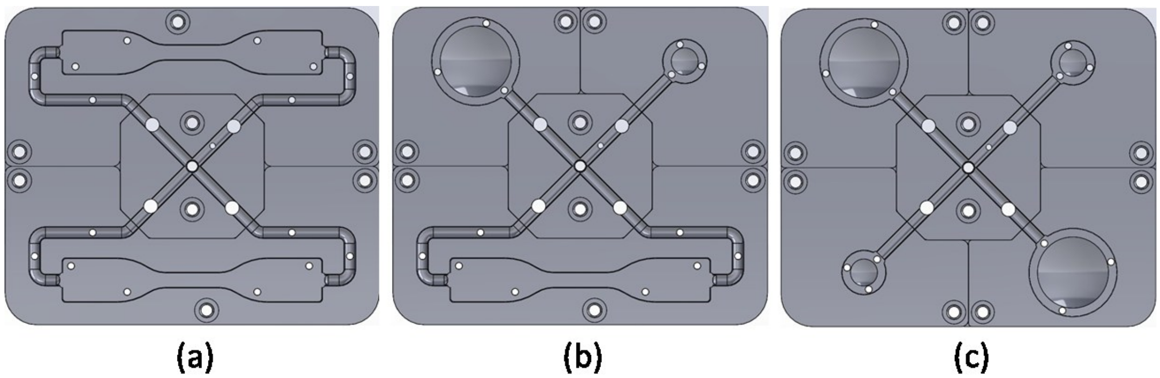


Figure 4-21: Modular Cavity Inserts Assembly - (a) Two Cavities (b) Three Cavities (c) Four Cavities

Because the modular melt modulation system is designed to control both melt flow during filling and packing pressure, the system is equipped with a pressure transducer. A pressure transducer, model number 6159A, made by Kistler has been selected and shown in Figure 4-22.

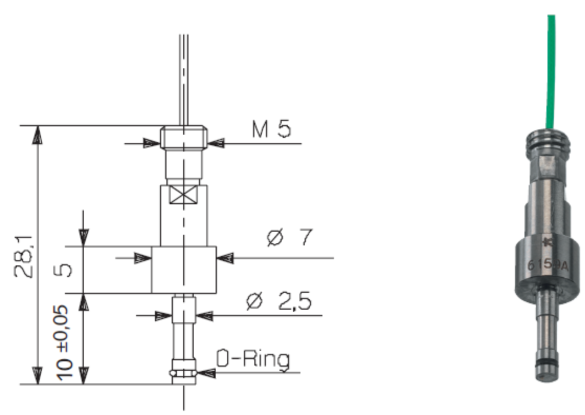


Figure 4-22: Kistler Pressure Transducer (Model No. 6159A) [50]

This model is designed specifically to measure cavity pressure. The pressure transducer technical data is presented in Table 4-4.

Table 4-4: Technical Data of Kistler Pressure Transducer Model 6159A [50]

Specification	**Unit**	**Value**
Range	bar	0-2,000
Overload	bar	2,500
Sensitivity	pC/bar	≈ -2.5
Linearity, all ranges	% FSO	≤ ±1
Operating Temperature Range		
Mold (sensor, cable, connector)	C	0-200
Melt (at front of sensor)	C	< 450

Figure 4-23 illustrates the valve locations. Since the pressure transducer is on the same runner as valve #1, the first cavity insert must be attached to valve #1 at all times, regardless of the required application.

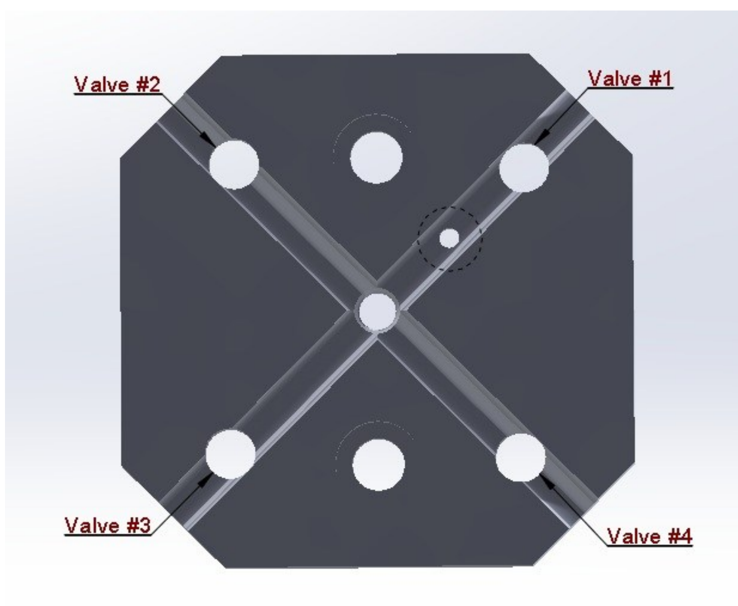


Figure 4-23: Valve Insert

In order to incorporate the modular melt modulation system to a mold assembly, where the cavity inserts share the same ejector pins, the following minor modifications will be required:

1. Drill through holes for the valves through the B-plate, support plate (if applicable), ejector retainer plate, and the ejector plate.
2. The B-plate must also have a through hole for the pressure transducer.
3. Drill four mounting holes (for the valve driving mechanism) on the ejector plate.
4. Install the extension bars (2.5 inches minimum width), similar the one shown in Figure 4-6, between the ejector housing and the B-plate to make room for the valve driving mechanism.
5. Replace the four mounting bolts that secures the ejector housing to the mold assembly with longer bolts to compensate for the extension bars length.

If, on the other hand, the cavities are dissimilar or require ejector pins at different locations, the new design of the cavity inserts (not shown here) and a new B-plate will be required in addition to the modifications listed above. The new cavity insert design is an assembly that has its ejector pins and springs. Therefore, it requires a special B-plate and the ejector retainer plate and the support plate will not be required.

Installation of the valve driving mechanism is shown in Figure 4-24.

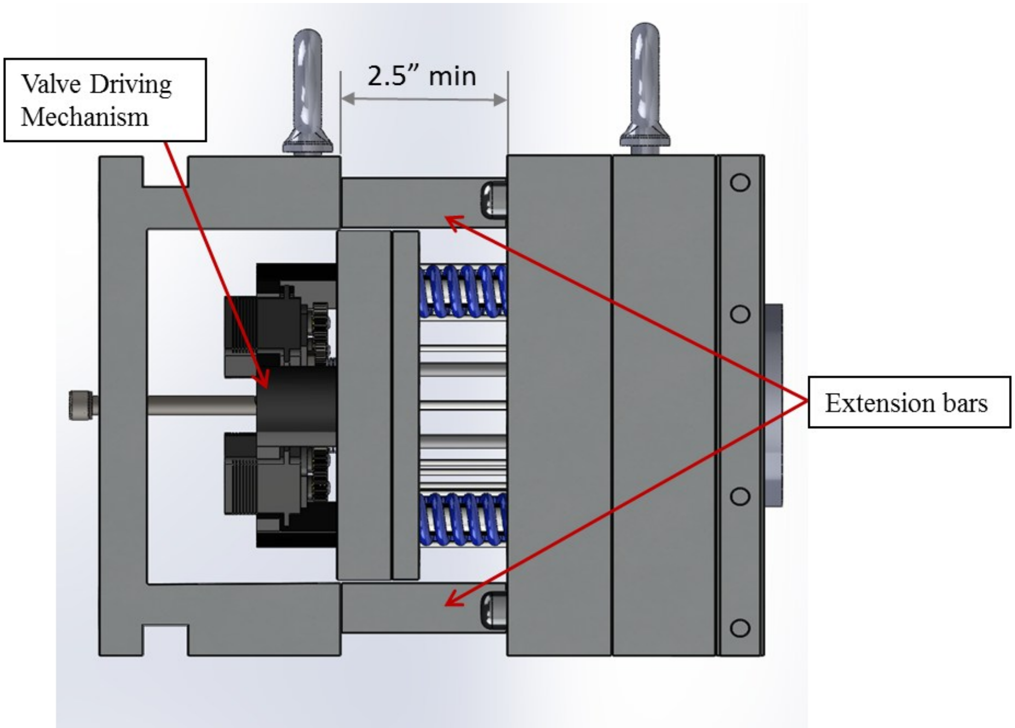


Figure 4-24: Modular Mold Plate – Driving Mechanism Location

4.2.3 User Interface Control (UIC)

The modular melt modulation system is controlled by a user interface control (UIC) unit, which is fully integrated and designed to be a stand-alone unit. The current prototype (shown in Figure 4-25 and Figure 4-26) requires an external (AC) power source, but no PC is required to operate it. The purpose of the UIC is to allow the operator to choose the type of control required for each job. This UIC is designed to control up to, but not limited to, four valves simultaneously. Additional valves can be added if an expansion of the system is required. The microcontroller has 36 possible control scenarios to control up to four valves. Adding more valves to the system will require more power and additional lines of code to address new control scenarios, not including functions for manual control. Each valve position can be controlled precisely and the controller has LEDs showing the status of each valve, whether it is on or off.

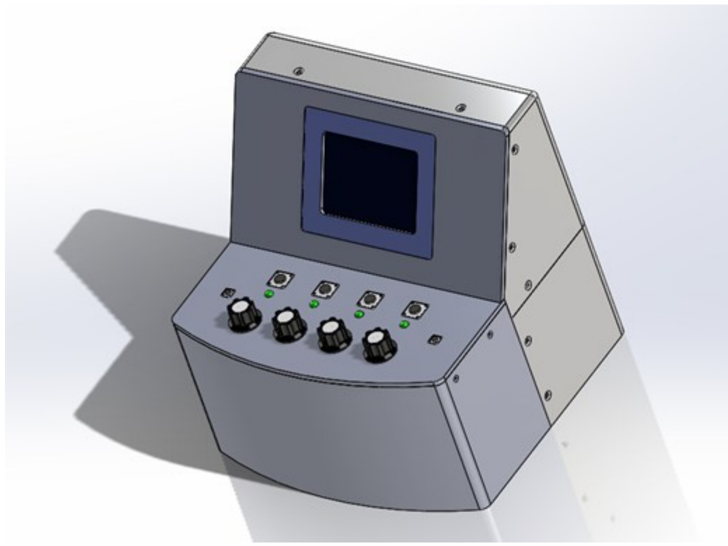


Figure 4-25: User Interface Control (UIC)

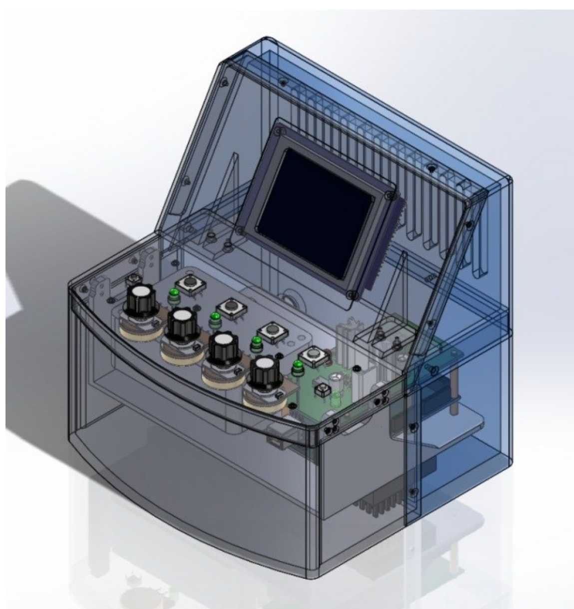


Figure 4-26: User Interface Control (UIC) – Transparent View

The UIC consists of the following major units:

1. TFT LCD Touch screen display
2. Microcontroller and main PCB board
3. Voltage regulators/amplifier/other electronic components

4.2.3.1 **TFT LCD Touch Screen**

The display used for the prototype is a 3.2” TFT LCD touch screen module as seen in Figure 4-27. It is designed with a touch controller and, through a shield, is compatible with the Arduino MEGA, which is an open source platform. This LCD touch screen was selected because of its ability to perform required tasks at a reduced cost.

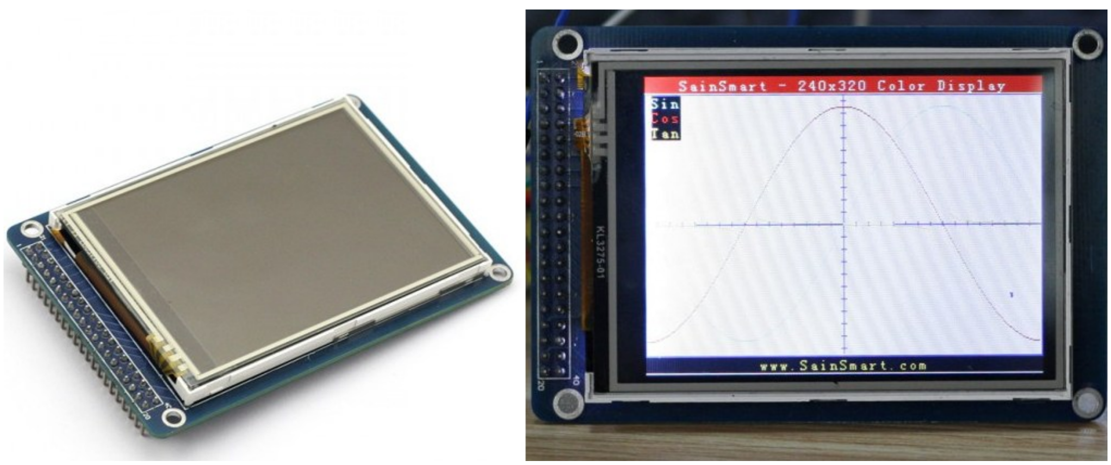


Figure 4-27: Touchscreen LCD [44]

4.2.3.2 **Microcontroller and Main PCB Board**

The Microcontroller used for the modular melt modulation prototype is the Arduino Mega, shown in Figure 4-28 and Figure 4-29. The Arduino is an open source (free to download) platform based on a simple input/output (I/O) board and a development environment that implements the Processing language [46]. The Arduino Mega has 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button [45]. The Arduino MEGA board schematic can be viewed in [51]. Other Arduino tools and resources can be found in [52] and [53].

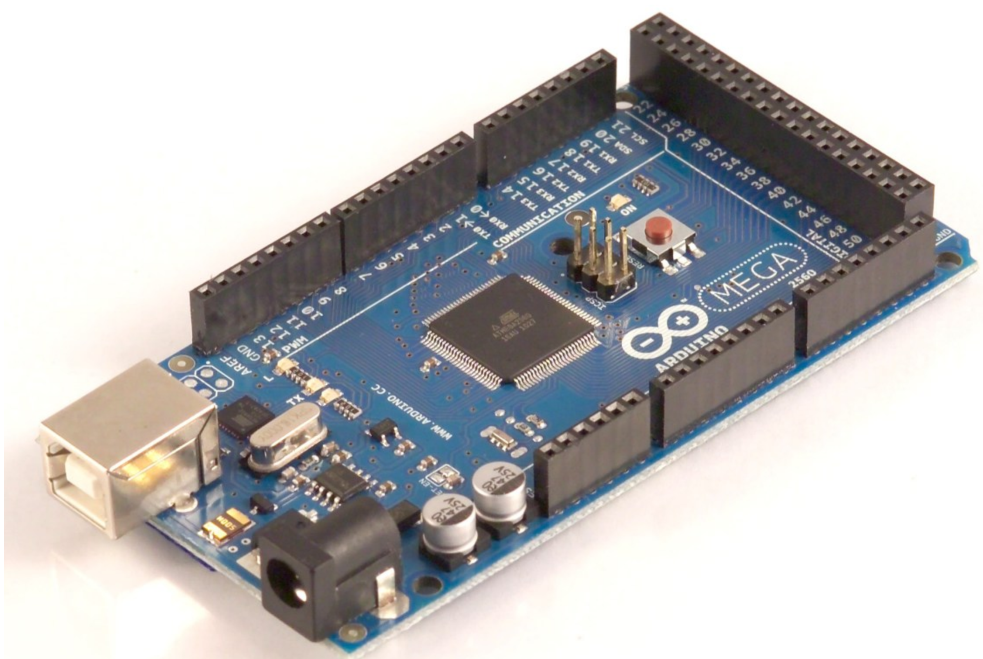


Figure 4-28: Arduino Mega Microcontroller [45]

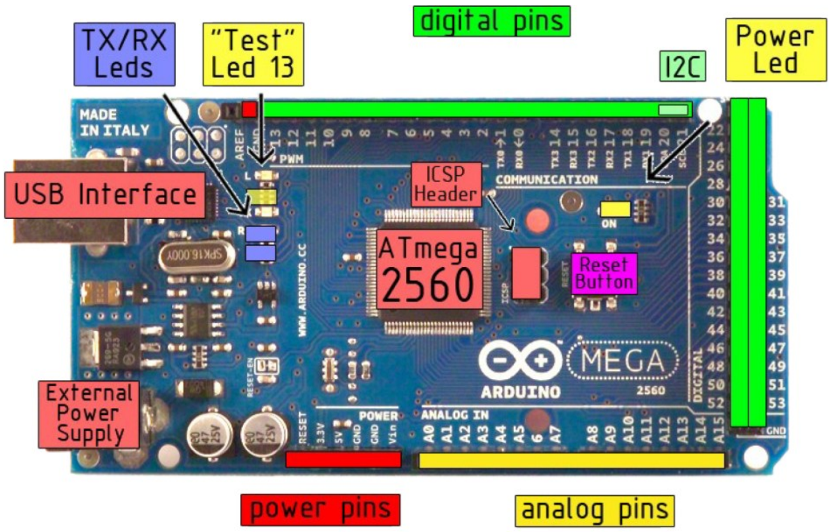


Figure 4-29: Arduino Mega - Labeled Components [45]

The ATmega1280 has 128 KB of flash memory for storing and it allows the user to upload new code without use of an external hardware programmer. It communicates using the original STK500 protocol (C header files).

The Mega has 54 digital pins that can be used as an input or output. Some of the pins have specialized functions, but all operate at 5 volts. Each pin can provide or receive a maximum of 40 mA and has an internal pull-up resistor of 20-50 kOhms [45]. The Arduino Mega can be programmed with the Arduino software that is free to download (http://arduino.cc/en/Main/Software). The ATmega1280 on the Arduino Mega

The Arduino Mega can be powered by connecting to a computer with a USB connection or with an external power supply and the power source is selected automatically. External (non-USB) power source can come either from an AC-to-DC wall or battery. The recommended power range for the Arduino Mega is 7 to 12 volts. It can operate at external power source on a range of 6 to 20 volts. However, if less than 7V is supplied, the 5V pin may supply less than five volts and that might cause the board to be unstable. Also, if more than 12V is supplied, the built-in voltage regulator may overheat and damage the board. For the modular melt modulation prototype, an external power supply (PowerMax PM3-45), shown in Figure 4-30 is used along with voltage regulators to regulate the voltage supplied to the microcontroller and the servo motors. The characteristics of the power supply used are summarized in Table 4-5.

Figure 4-30: PowerMax PM3-45 – Modular Melt Modulation Power Supply

Table 4-5: Modular Melt Modulation Power Supply

Part Number	PM3-45
DC Output Voltage (No Load) approx.	13.2/13.6/14.4V
Output Amperage, Max Continuous	45amps
Maximum Power Output, Continuous	600 watts
Maximum AC Current @ 108VAC	5 Amps
Typical Efficiency	>85%
Fan Control	Proportional
Short Circuit Protection Thermal Protection	Yes
Dimensions	7.15X10.5X3.45
Weight	7.0 lbs

The Arduino platform has been selected because of the following features [47]:

- It is a multiplatform environment. It can run on all common platforms such Windows, Macintosh, and Linux.
- It is based on the Processing programming IDE, an easy-to-use development environment.
- It can be programmed via a USB cable, not a serial port. This feature is useful, because many modern computers do not have serial ports.
- It is open source hardware and software. This allows the user to download the circuit diagram, buy all the components, and make it their own, without paying anything to the makers of Arduino.
- The hardware is low cost with good quality. The Mega board costs about $35 and replacement parts are cheap and widely available. Replacing a burnt-out chip on the board costs no more than $7.
- There is a large and active community of users of Arduino, so there is plenty of online support available at no extra cost.
- The Arduino Project was developed in an educational environment and is therefore great for newcomers to get things working quickly.

The characteristics of the Arduino Mega board are summarized in Table 4-6.

Table 4-6: Modular Melt Modulation PCB Board Details

Microcontroller	ATmega1280
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	54 (of which 15 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	128 KB of which 4 KB used by bootloader
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz

4.2.3.3 Control Logic

The control logic defines the specifics of the operations and the code is embedded in the microcontroller. The current code allows for two modes of control; manual and automatic. In the manual model, each control valve is turned by a dial knob to a fixed angle until it is changed again. The automatic control has several program scenarios to control up to four valves to perform the following:

1. Balance melt flow for Single and multi-cavity
2. Produce high quality family molding parts
3. Weld-line position control
4. Packing pressure and packing time control

CHAPTER 5 – NUMERICAL SIMULATIONS AND INVESTIGATION OF COLD RUNNER INJECTION MOLDING PROCESSING PARAMETERS AND THEIR EFFECTS ON PRODUCT OPTICAL PROPERTIES

5.1 Introduction

This chapter investigates the effect of packing processing parameters (packing pressure and time) of cold runner based injection molding on the final product quality. Injection molding packing processing parameters have a significant impact on the polymer internal molecular orientation, mechanical properties and optical performance. Numerical simulations of common thermoplastic clear polymers have been completed and the results are presented herein [55].

This study is comprised of two parts. First is numerical simulation, using Moldflow software, to investigate the quality of the molded product in terms of geometric dimension tolerance, while the second part is a set of experiments to show the variation of optical quality and physical strength due to different processing conditions. The numerical simulations presented here were completed based on a single-cavity mold. The experimental results are discussed in CHAPTER 7.

The primary goal of this study was to investigate processing parameters and their impact on the properties of injection-molded products. The results have been used to establish a baseline to expand current melt modulation capabilities, including enhancing optical properties of clear polymers in cold runner based injection molding.

5.2 Materials

The three optical polymers selected for the numerical simulation are Polymethyl Methacrylate (PMMA), Polycarbonate (PC), and General Purpose Polystyrene (GPPS). PMMA has a trade name of Plexiglas® V-920 and is manufactured by Arkema, Inc. Polycarbonate (PC), known as LEXAN™ 101, is manufactured by SABIC. General Purpose Polystyrene (GPPS) is made by Americas Styrenics and also called STYRON® 685D. Table 5-1 shows some of the properties such as melt density, specific heat, and thermal conductivity of the materials used for simulation and testing.

Table 5-1: Properties of PMMA, PC, and GPPS [43]

Polymer	Melt Density g/cm^3	Specific Heat (Cp) J/kg/°C	Thermal Conductivity W/M/°C
PMMA (at 246ºC)	1.0606	2638	0.163
PC (at 300ºC)	1.0477	1900	.24
GPPS (at 200ºC)	.97096	1768	.123

Dog-bone shaped parts made in accordance with ASTM D638 – Type I were used for this study. The geometry and dimensions of the test specimens are shown in Figure 5-1. This figure also shows the three different nodes used for the numerical simulation and the experiment. Node 40, node 102, and node 178 are positioned at 17.58 mm, 84.66 mm, and 148.76 mm away from the gate in an axial direction respectively. These three nodes and gate positions are used to measure volume shrinkage, deflection and other parameters referenced in the simulations and experimental results.

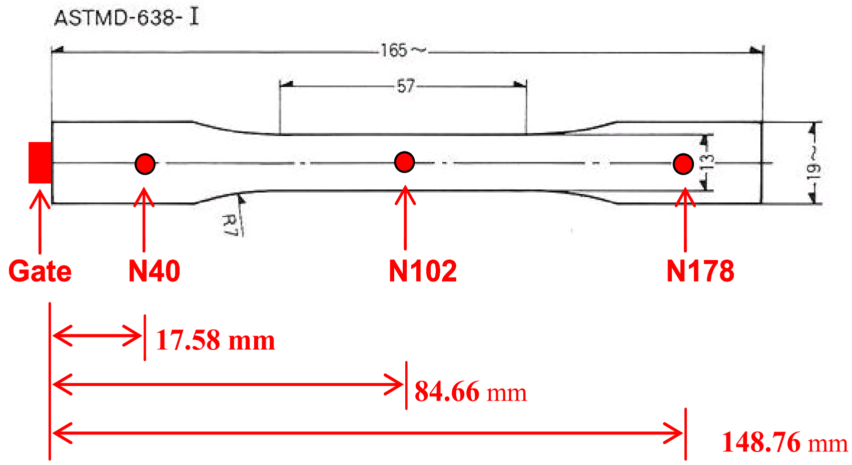


Figure 5-1: Gate and Nodes Position

The injection molding machine used to conduct the experiment was a Nissei model PS40E5ASE. Table 5-2 lists some of the machine's key specifications.

Table 5-2: Nissei Injection Unit Specifications [48]

Specification (unit)	**Value**	**Specification (unit)**	**Value**
Screw Diameter (mm)	26	Injection Rate (cm^3/sec)	71
Injection Capacity (cm^3/shot)	49	Screw Stroke (mm)	92
Plasticizing Rate (kg/hr)	22	Screw Speeds (rpm)	0-335
Injection Pressure (kg/cm^2)	1870	Clamp Force (ton)	40

5.3 Numerical Simulation

The purpose of the numerical simulations studied and reported here was to investigate the influence of the processing parameters on weight and geometric dimensional quality, including shrinkage, and deflection. The analysis was performed using Moldflow. The simulation focused on a dog-bone shaped part molded from PMMA, PC and GPPS material. A 3-D model was created, along with the runner system and represented in Figure 5-2. The 3-D model was meshed, creating 5,245 elements connected by 1,029 nodes. The total volume of the dog-bone cavity and the cold runner system, including the sprue, are 8.1427 cm^3 and 8.8439 cm^3 respectively.

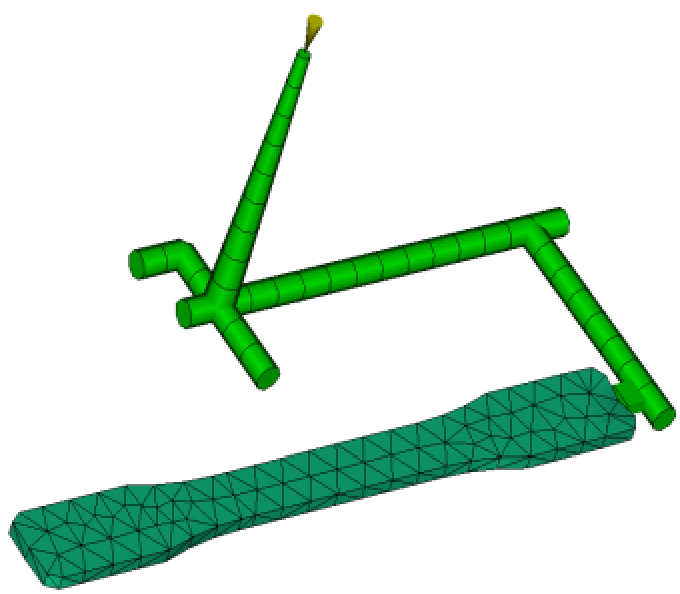


Figure 5-2: A 3-D Meshed Model in MOLDFLOW

To analyze the effect of each parameter, the Taguchi method with an L9 (3^4) orthogonal array was used to conduct the simulation by setting four parameters to have three levels each. Table 5-4 shows all corresponding levels for each parameter selected for L9 array in Table 5-3.

Table 5-3: L9 (3^4) Orthogonal Array

Experiment	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	2	3	1
5	2	3	1	2
6	2	1	2	3
7	3	3	2	1
8	3	1	3	2
9	3	2	1	3

Table 5-4: Parameters Used for Numerical Simulation

Material	Parameter	Symbol	Level 1	Level 2	Level 3
PMMA	Mold Temperature (°C)	A	38	58	80
	Packing Pressure (MPa)	B	30	75	120
	Packing Time (s)	C	2	8	15
	Melt Temperature (°C)	D	240	260	280
PC	Mold Temperature (°C)	A	80	91	102
	Packing Pressure (MPa)	B	30	75	120
	Packing Time (s)	C	2	8	15
	Melt Temperature (°C)	D	286	296	324
GPPS	Mold Temperature (°C)	A	30	45	60
	Packing Pressure (MPa)	B	30	75	120
	Packing Time (s)	C	2	8	15
	Melt Temperature (°C)	B	198	219	240

The virtual injection molding machine in Moldflow was set up to operate with the actual Nissei machine parameters, shown in Table 5-2, with an injection speed 20 cm^3/s, 40 tons of clamping force, and velocity/pressure (V/P) switchover at 95% volume filled. Cooling time was set to 150 seconds to ensure complete solidification. The results were selected from the three different node positions illustrated in Figure 5-1.

5.3.1 Average Volumetric Shrinkage Results

Volumetric loss (shrinkage) is the increasing percentage of volume lost from the time packing phase ends until the part reaches ambient reference temperature. High volumetric shrinkage is a common quality problem in injection molding parts and often results in sink marks and voids. Also, non-uniform volumetric shrinkage may cause warping. The results of average volumetric shrinkage for PMMA, PC, and GPPS are presented in Figure 5-3, Figure 5-4, and Figure 5-5 respectively.

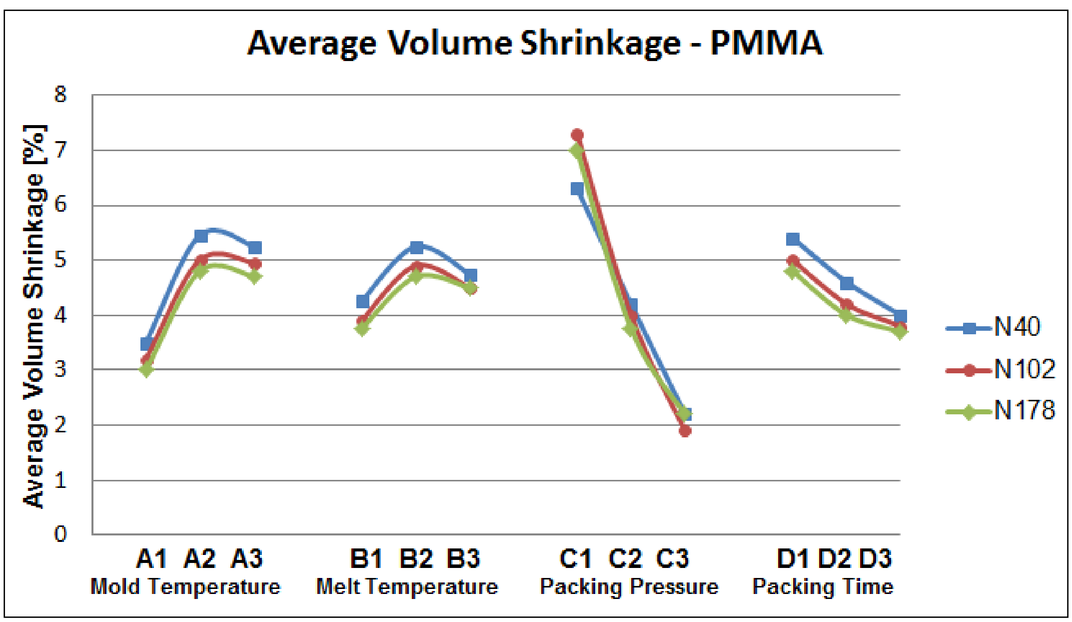


Figure 5-3: Average Volumetric Shrinkage of PMMA (ASTM D-638 Type I)

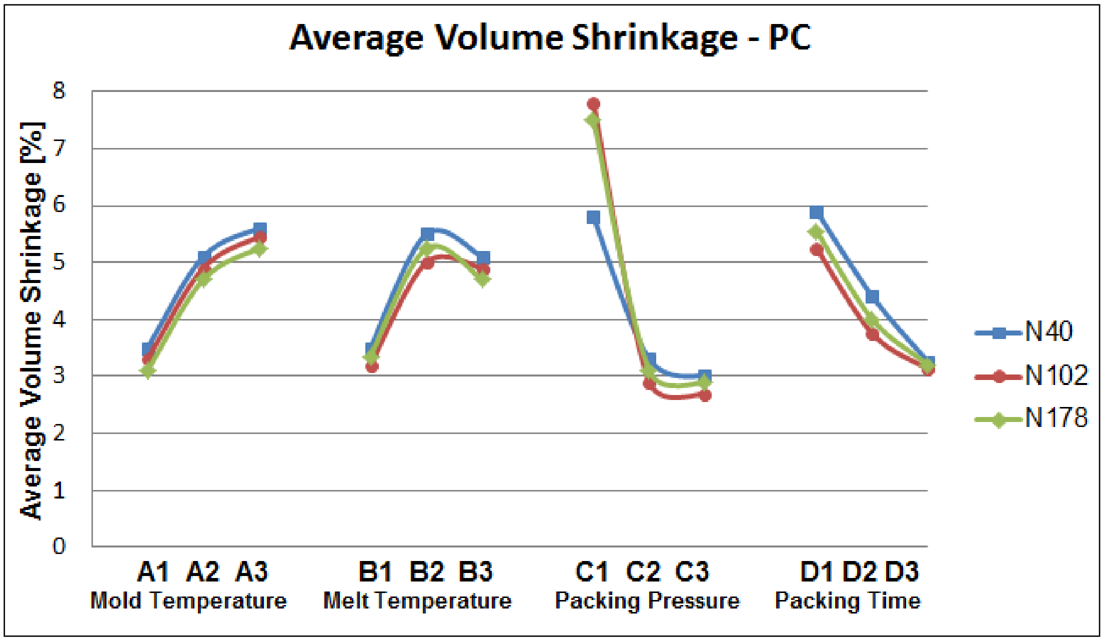


Figure 5-4: Average Volumetric Shrinkage of PC (ASTM D-638 Type I)

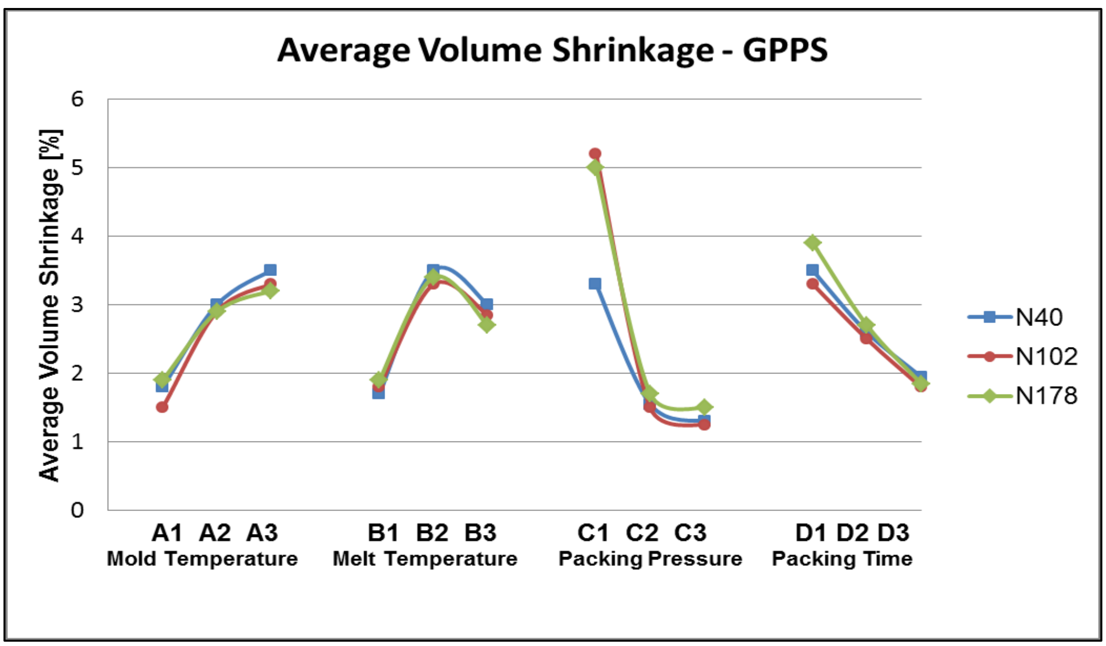


Figure 5-5: Average Volumetric Shrinkage of GPPS (ASTM D-638 Type I)

5.3.2 *Deflection Results*

Deflection is determined by the part stiffness and the level of non-uniform shrinkage. Common causes of warpage are non-uniform shrinkage, and unbalanced cooling [30] [56]. The effect of non-uniform shrinkage on warpage is minor when compared to unbalanced cooling. The non-uniform shrinkage can be reduced by increasing the packing parameters, including packing pressure and time. However, this can result in greater warpage from unbalanced cooling [56].

For this simulation, the mold temperature was set at constant without internal cooling lines. Thus, it can be assumed that there was no deflection from unbalanced cooling and the cooling rate in all simulation results was constant throughout the part. An overall deflection measurement is represented as the total warpage in each node. The Taguchi results of the total deflection in all directions for PMMA, PC, and GPPS are presented in Figure 5-6, Figure 5-7, and Figure 5-8 respectively.

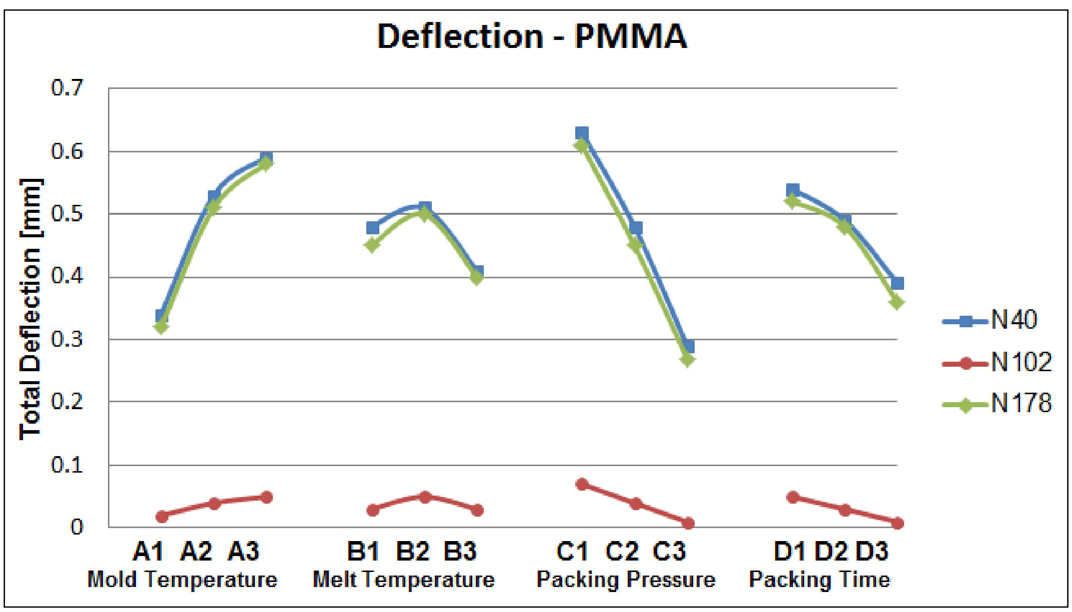


Figure 5-6: Total Deflection of PMMA - ASTM D-638 Type I (Numerical)

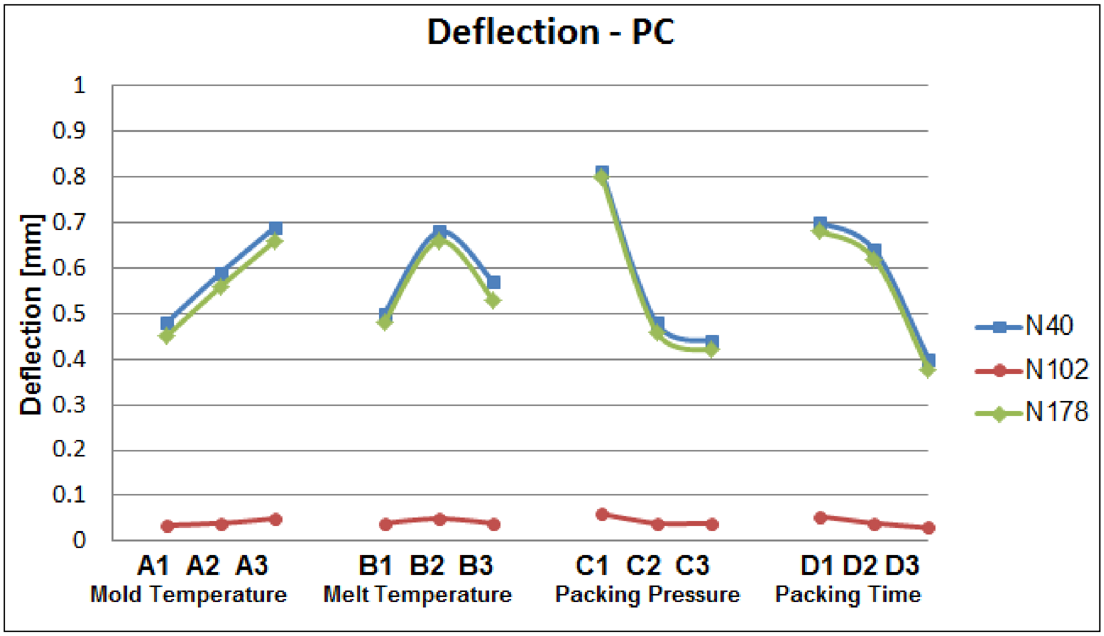


Figure 5-7: Total Deflection of PC - ASTM D-638 Type I (Numerical)

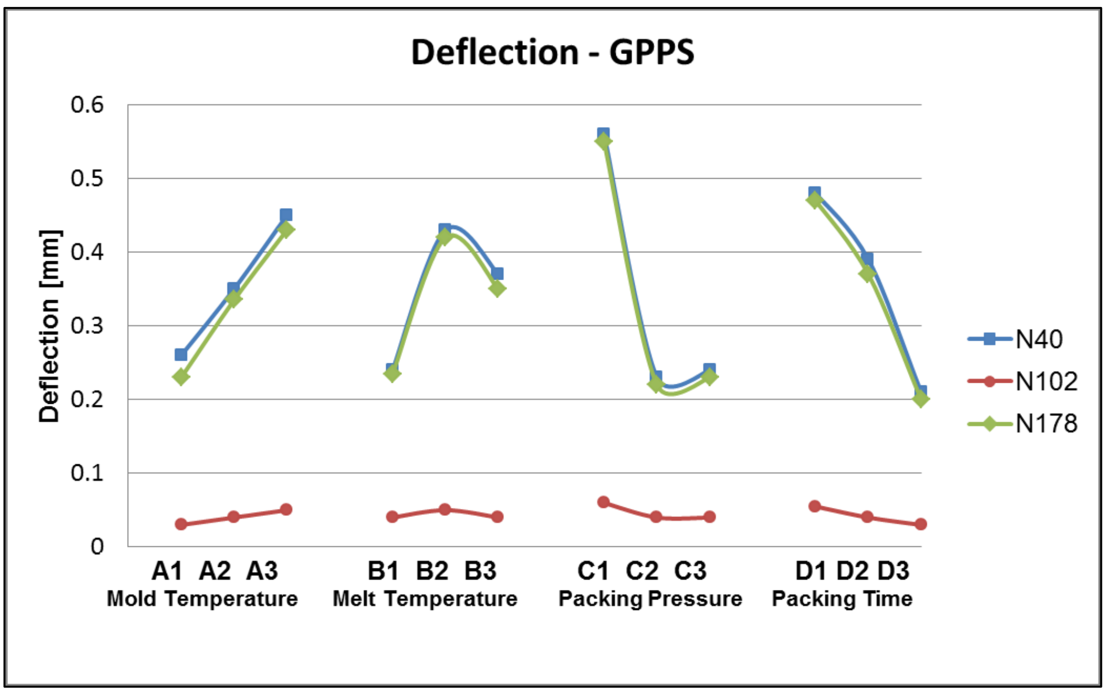


Figure 5-8: Total Deflection of GPPS - ASTM D-638 Type I (Numerical)

5.3.3 Weight

Part final weight is a critical quality property, especially for small components used in aerospace and electronics applications. The Final weight simulation results of all three transparent materials are shown in Figure 5-9.

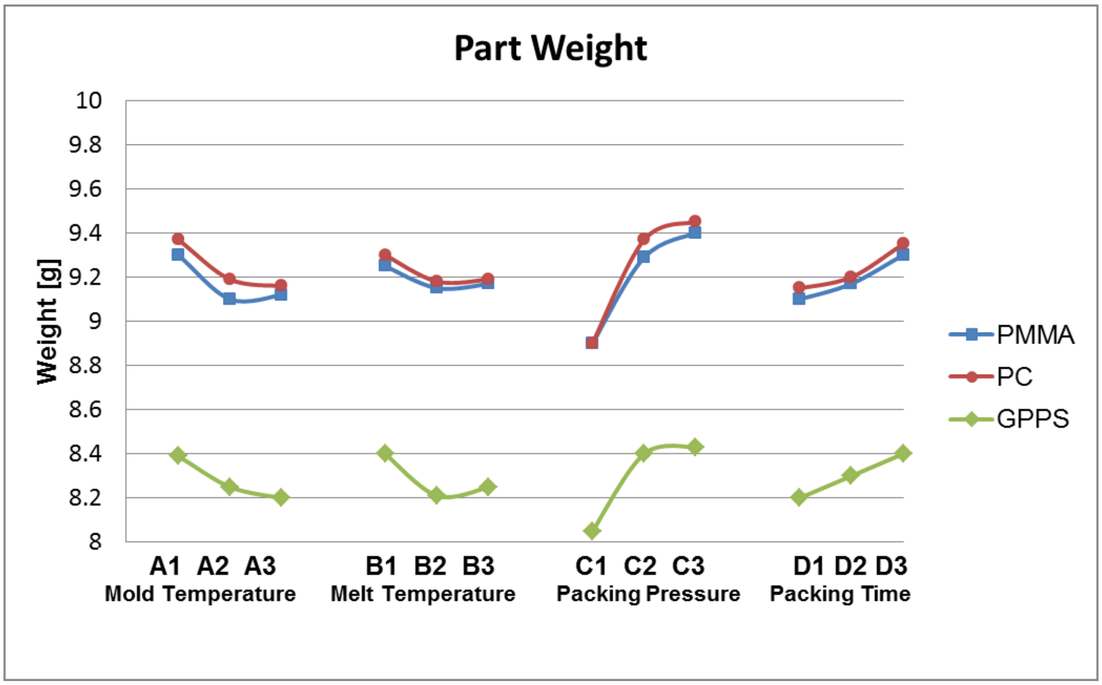


Figure 5-9: Final Part Weight - ASTM D-638 Type I (Numerical)

5.4 Discussion

The results presented here clearly show that processing parameters significantly impact the properties of molded product. Parameters such as melt and mold temperature can have a direct impact on the final properties and quality of the molded product. Higher temperature provides the melt flow more relaxation time before it solidifies. Longer relaxation time leads to material with less residual stresses, less birefringence, and less retardation. On the other hand, higher temperatures may degrade the material and lead to a weaker part as well as inducing more volume loss (shrinkage) and deflection.

Other parameters such as packing pressure and packing time also affect product quality. Increasing packing parameters tends to reduce volume loss (shrinkage) and deflection. However, it increases the product final weight. In addition, increasing packing pressure and packing time causes higher molecular orientation, which is evidenced through higher birefringence and optical retardation. Products with higher molecular orientation in the flow direction exhibit higher tensile strengths. On the contrary, high birefringence causes poor optical characteristics such as haze or focal blur.

Similar investigation has been conducted using the melt modulation technique to analyze the impact of modulating the melt flow and the packing pressure on optical and physical properties of cold runner based injection-molded products. The numerical simulations results are detailed in the next chapter.

CHAPTER 6 – NUMERICAL ANALYSIS AND INVESTIGATION OF MELT MODULATION CONTROL AND ITS EFFECT ON COLD RUNNER INJECTION MOLDING PACKING PARAMETERS AND FINAL PRODUCT QUALITY

6.1 Introduction

Transparent polymers with good optical properties are commonly used for plastic optics applications. The most widely used polymers are Polymethyl Methacrylate (PMMA) and Polycarbonate (PC) due to their excellent optical properties, lighter weight, lower cost and higher impact resistance when compared with glass.

There are two main factors that can significantly affect the quality of clear plastic materials. First is birefringence, and the second is geometric dimension changes from the desired shape. High birefringence can cause poor optical characteristics such as haze or focal blur. Major dimensional problems that could occur in injection molded optics are shrinkage, warpage, and surface quality. The shape quality of molded optics depends primarily on the processing parameters of the injection molding cycle, including melt temperature, mold temperature, packing pressure, and packing time.

The primary goal of this study is to investigate the impact of melt modulation on optical and physical properties of cold runner based injection-molded products. The melt modulation technique has been be implemented to control the packing processing parameters (packing pressure and packing time), and determine the optical quality in terms of both precision of geometric dimensions and optical birefringence. Numerical simulations of common thermoplastic optical polymers, using the melt modulation technique, have been performed to investigate the quality of the molded part in terms of geometric dimension tolerance. The results provided a baseline to expand current melt modulation capabilities to enhance optical properties of clear polymers [65]. The optical briefings results are discussed in CHAPTER 7.

6.2 Materials

Three common optical polymers were chosen for the numerical simulation; Plexiglas® V920 (PMMA), LEXAN™ 101-111 (PC), and STYRON® 685D (GPPS). Table 5-1 shows key properties such as melt density, specific heat, and thermal conductivity of the materials used for simulation and testing.

Dog-bone shaped parts made in accordance with ASTM D638 – Type IV have been used for this study. The geometry and dimensions of each dog-bone cavity are presented in Figure 6-1.

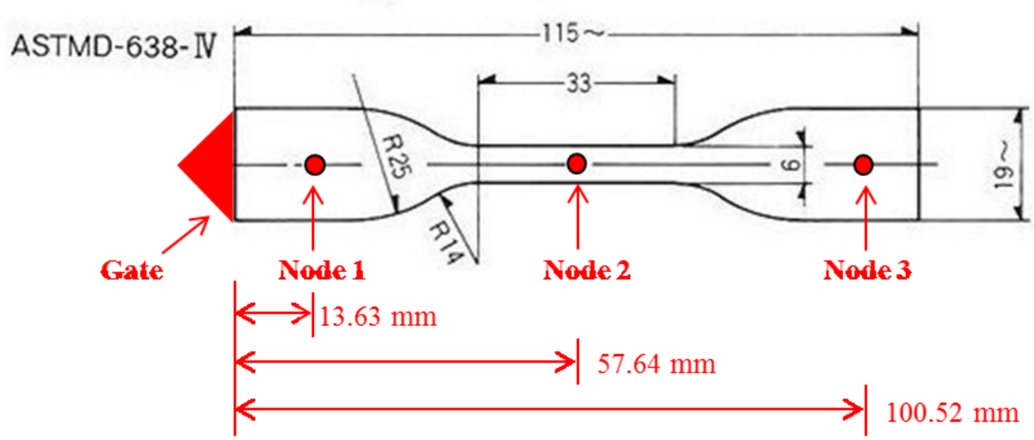


Figure 6-1: Gate and Nodes Position ASTM D638 – Type IV

6.3 Numerical Simulation

The virtual injection molding machine in Moldflow was set up to operate with the actual parameters of the Nissei injection molding machine as shown in Table 5-2. Three packing pressure values were selected for the numerical simulation; 55MPa, 82.5MPa, and 110MPa, which represents 30%, 45% and 60% of the maximum pressure of the Nissei machine respectively. An injection rate of 35cm^3/s was set to a packing time of 15 seconds, a clamping force of 40 tons, and V/P switchover at 95% volume filled. Cooling time was set to 150 seconds to ensure complete solidification of the part. The processing parameters have been set according to the values listed in Table 6-1.

Table 6-1: Recommended Processing Conditions for PMMA, PC and GPPS [58]-[60]

Processing Parameter	Unit	PMMA (Plexiglas® V920)	PC (LEXAN™ 101)	GPPS (STYRON® 685D)
Barrel Zone 1 Temperature (Feed)	°C	204	290 - 310	200 - 215
Barrel Zone 2 Temperature (Middle)	°C	210	300 - 320	215 - 230
Barrel Zone 3 Temperature (Front)	°C	216	310 - 330	230 - 245
Nozzle Temperature	°C	210	305 - 325	230 - 245
Mold Temperature	°C	65 - 85	80 - 115	15 - 65
Melt Temperature	°C	240 - 280	310 - 330	193 - 232
Back Pressure	MPa	0.7 – 1.4	0.3 - 0.7	0.2 – 1.5
Injection Pressure (% of Maximum)	%	50	50	50
Screw Speed	RPM	50 - 100	40 - 70	Medium - High
Molding Shrinkage	%	0.4 - 0.7	0.5 – 0.7	0.3 - 0.7

The study was performed using Autodesk Simulation Moldflow. 3-D models with parabolic runners and fan gates were created and imported into Moldflow as illustrated in Figure 6-2.

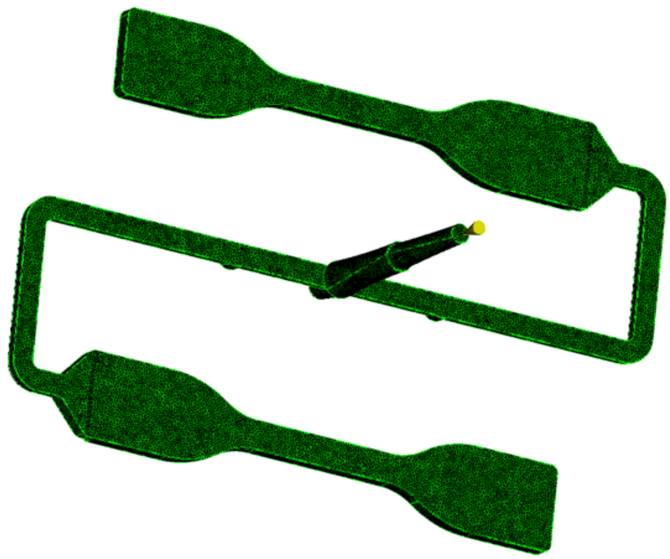


Figure 6-2: A 3-D Meshed Model in MOLDFLOW

Three analyses have been conducted to complete this study. The first analysis is to determine the optimal location of the control valves in the runner. The second analysis is to investigate the effect of the melt modulation technique on product quality. The results include the pressure drop across the valve at different valve angles with varied packing pressure, the average volume shrinkage percentage, and the total deflection of the final product. The last analysis evaluates the shear rate of the three polymers as a result of turning the control valve.

The model used for the study has two pressure sensors. Figure 6-3 shows the location of each pressure sensor. The first pressure transducer (P1) is located near the sprue. The second pressure transducer (P2) is positioned near the gate.

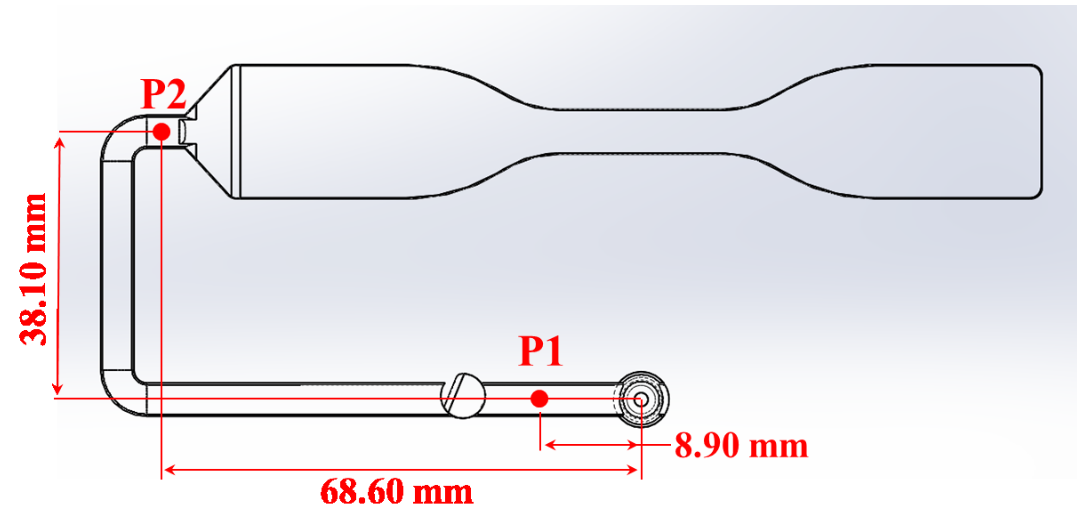


Figure 6-3: Pressure Transducer Positions

6.3.1 Control Valve Optimal Location

This analysis was completed to establish an optimal location for the control valves. Four numerical simulations were completed, one simulation for each control valve location. Since the model was symmetrical, only one side was used for the analysis. Four possible control valve locations have been considered, and they are shown in Figure 6-4. The first location is nearest to the sprue. Since a pressure transducer is required to be installed between the control valve and the sprue, the first valve was located about 25.4mm (1.0”) away from the sprue. The second control valve was positioned at 50.8mm (2.0”) away from the sprue. The third location was between the sprue and the gate. The last valve was located near the gate.

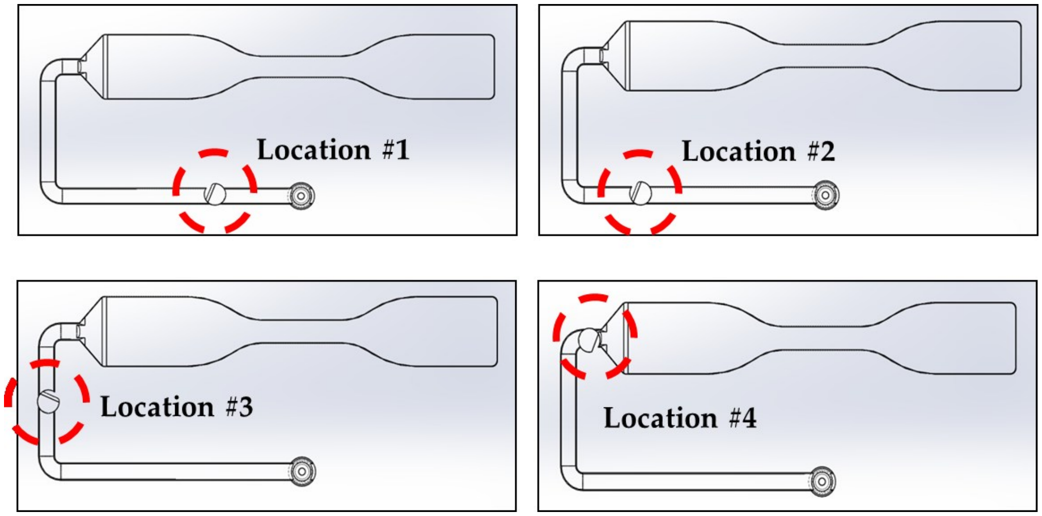


Figure 6-4: Four Possible Valve Locations

6.3.2 Melt Modulation Effect on Optical and Physical Properties

Since it is not feasible to analyze a transient process in Moldflow, such as turning the control valve during each simulation cycle, three separate models with different control valve angles were created; θ = 0˚, θ = 33.75˚, and θ = 67.5˚, as shown in Figure 6-5. In the first case, θ = 0˚, the control valves are fully open and there is 100% flow through the runner, and this one is referred to as the "100% model". In the second scenario, one control valve is completely closed through the filling and packing cycle while the other is partially closed with 62.5% melt flow through the runner or a control valve angle (θ) of 33.75˚. This one is denoted in the analysis as the "62.5% model". The reason for keeping one valve fully closed throughout the cycle is to avoid unbalanced filling during filling phase.

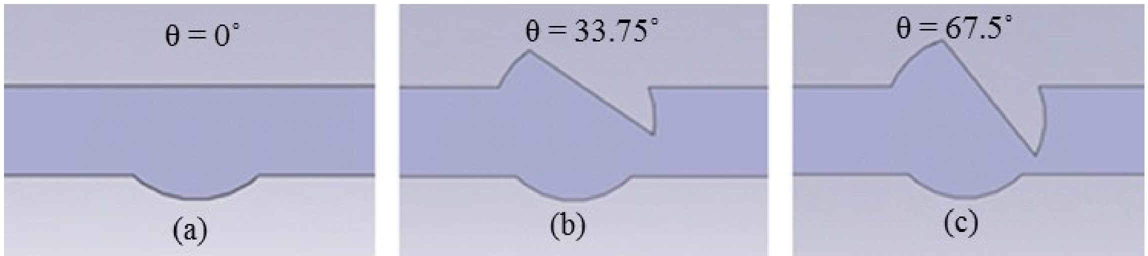


Figure 6-5: Runner System and Control Valve Positions
(a) 100% model (fully open) (b) 62.5% model (partially closed) (c) 25% Model (near closed)

The valve range of operation is from 0˚ to 90˚ relative to the runner center line. However, to avoid discontinuity in the runner system and high shear rate, it is desirable to restrict the control valve so that it returns to a position that is less than 90˚ during the packing phase. As a result, the control valve maximum range during packing stage has been limited to an angle, θ, of 67.5˚. This is illustrated in Figure 6-5(c) and is referred to as near closed position or the "25% model". In this case, there is only 25% flow through the runner. Table 6-2 summarizes the three valve positions used for the numerical simulations. Also, the geometry of the control valve is concentric. The parameters of the eccentric valve port used for this study are listed in Table 6-3.

Table 6-2: Control Valve Parameters

Parameters	θ_1	θ_2	θ_3
Control Valve Angle	0°	33.75°	67.5°
Valve Flow	100%	62.5%	25%
Valve Position	Fully Open	Partially-Closed	Near-Closed

Table 6-3: Parameters of Eccentric Valve Port

Parameter (units)	*Values*
Valve Radius, R (in)	0.125
Half of Runner Width, r (in)	0.0825
Offset Distance, s (in)	0.02
Range of Operating Angle, θ (degree)	90
Curvature l_1 (in)	0.293
Curvature l_2 (in)	0.149
Valve Seating distance, α (in)	0.0225

All models were meshed using 3D tetrahedral elements to achieve the most accurate results. For the fully open valve position (100% model), a 0.7 mm global edge length was applied. The total meshed tetras were 547,642 elements connected by 108,465 nodes. The partially closed valve model, Figure 6-5(b), has total meshed tetras of 379,836 elements and 72,410 connected nodes with a 0.5 mm global edge length. Last, the model for the near close valve position (25% model) has a 0.2 mm global edge length and 310,891 elements connected by 61,012 nodes.

6.3.3 Shear Rate Analysis

When the control valve is near the closed position, the maximum melt flow restriction has been reached. To determine of whether this flow restriction causes any degradation, the maximum shear rate had to be examined. Although the whole part was examined for excessive shear rate, the main focus was on the local areas where the control valve is located. The analysis evaluates the shear rate of the three different control valve models while subjected to three different packing pressures; 55MPa, 82.5MPa, and 110MPa, which represents 30%, 45% and 60% of the maximum pressure of the Nissei machine respectively.

6.4 Results and Discussion

The data presented in the following sections contain results of the pressure drop across the valve, the average volumetric shrinkage, the maximum deflection (warpage) of three different clear polymers, and the maximum shear rate at and around the control valve.

6.4.1 Pressure Drop across the Valve

This analysis determined the pressure drop across the valve with respect to several control valve locations, various control valve angles and different packing pressures. The pressure drop across the valve, ΔP, is calculated by subtracting P2 from P1. The first location, P1, is in the runner near the sprue and the second location, P2, is located just before the gate as illustrated in Figure 6-3.

6.4.1.1 Different Valve Locations

When the valve is fully open, there is little or no pressure drop across the valve. As the valve begins to turn, the pressure drop increases until the cycle reaches the end of the packing stage. In order to determine an optimal location for the control valve, the pressure drop across the valve at four possible locations was calculated from pressure data obtained from Moldflow. The numerical simulations were performed at two different packing pressures, 30% and 60% of the machines' maximum packing pressure respectively. Since all three selected polymers have similar behavior, only STYRON® 685D (GPPS) material was considered for the multi-valve location analysis and the control valve was set at the near closed-position (θ_3 = 67.5°). The results for the 30% of the maximum packing pressure are shown in Figure 6-6.

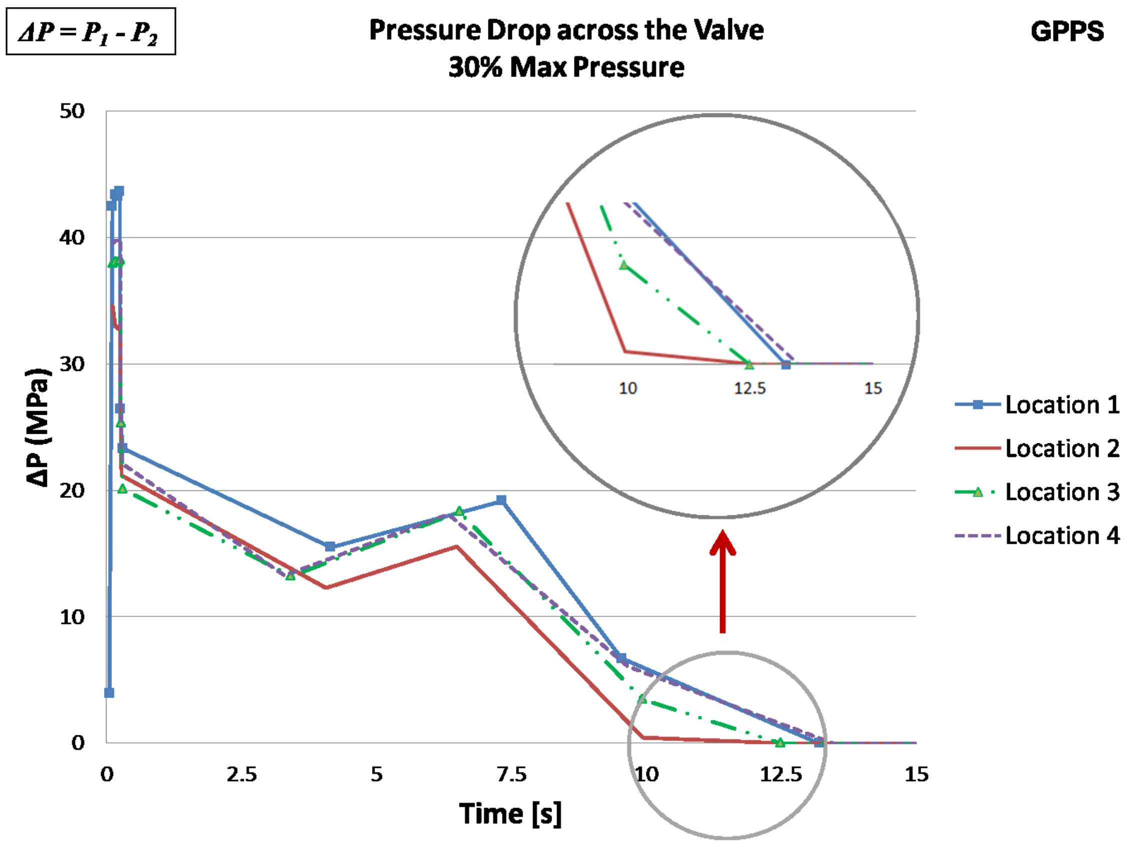


Figure 6-6: GPPS - ΔP across the Valve at Different Locations (30% Max Packing Pressure)

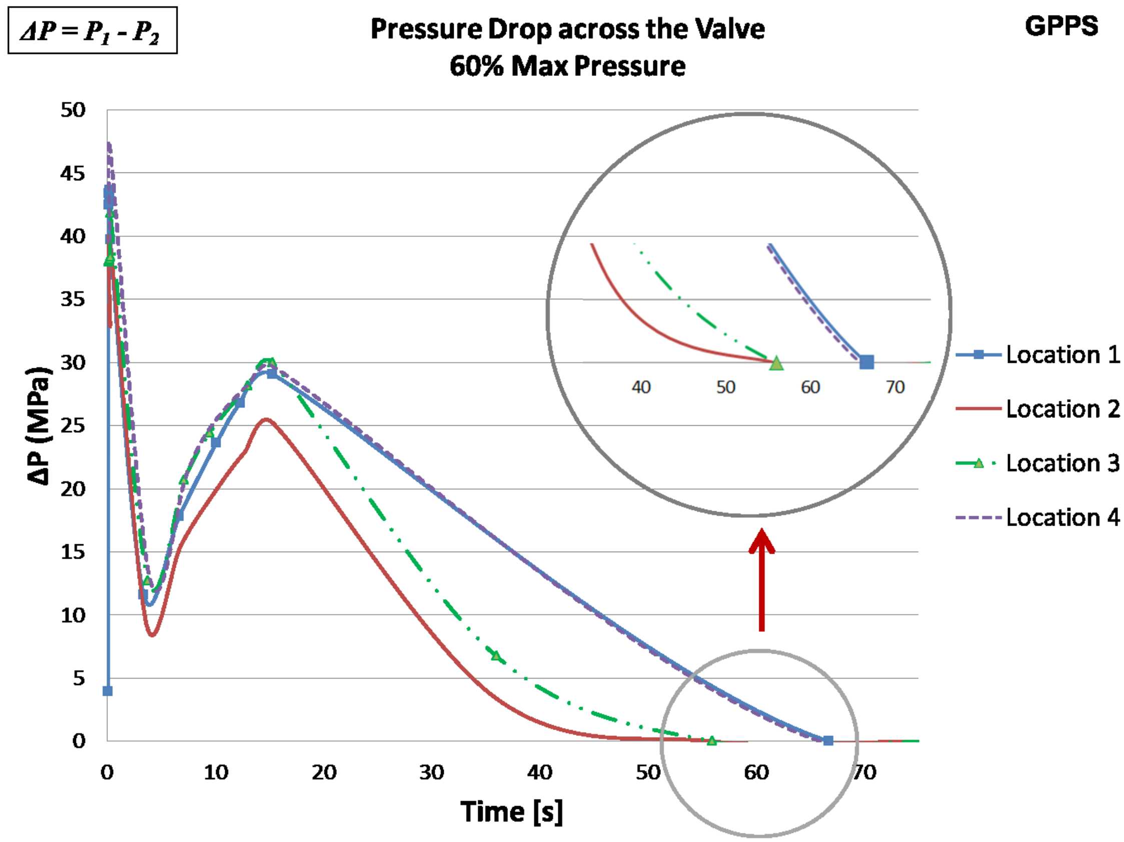


Figure 6-7: GPPS - ΔP across the Valve at Different Locations (60% Max Packing Pressure)

According to results, locations 1 and 4 have similar and higher pressure drop than the other two locations. When the packing pressure was set to 55Mpa, location 1 (nearest to the sprue) recorded the highest pressure drop throughout the filling cycle and most of the packing pressure phase. This indicates that location 1 has better packing pressure control and is therefore more effective in terms of final part quality control. This makes the first valve location more desirable than the other three. However, when the packing pressure was doubled, location 4 showed slightly higher packing pressure than location 1. Since it is more practical to have the pressure transducer near the sprue for the modular melt modulation system, valve location 1 was selected.

6.4.1.2 Different Valve Angles

The data presented here is for all the three different control valve models (25%, 62.5% and 100%) as a function of time from the beginning of the filling cycle (0.4 second) until the end of packing phase (15 second). The results for PMMA, PC and GPPS can be seen in Figure 6-8, Figure 6-9, and Figure 6-10 respectively. The numerical simulation was based on 110MPa packing pressures (60% of the machines' maximum packing pressure), and valve location 1. These results show the effects valve angle changes on the pressure drop across the valve. Increasing the control valve angle restricts the melt flow through the runner and also causes higher pressure drop. The highest pressure drop is seen near the close position of the valve (25% model).

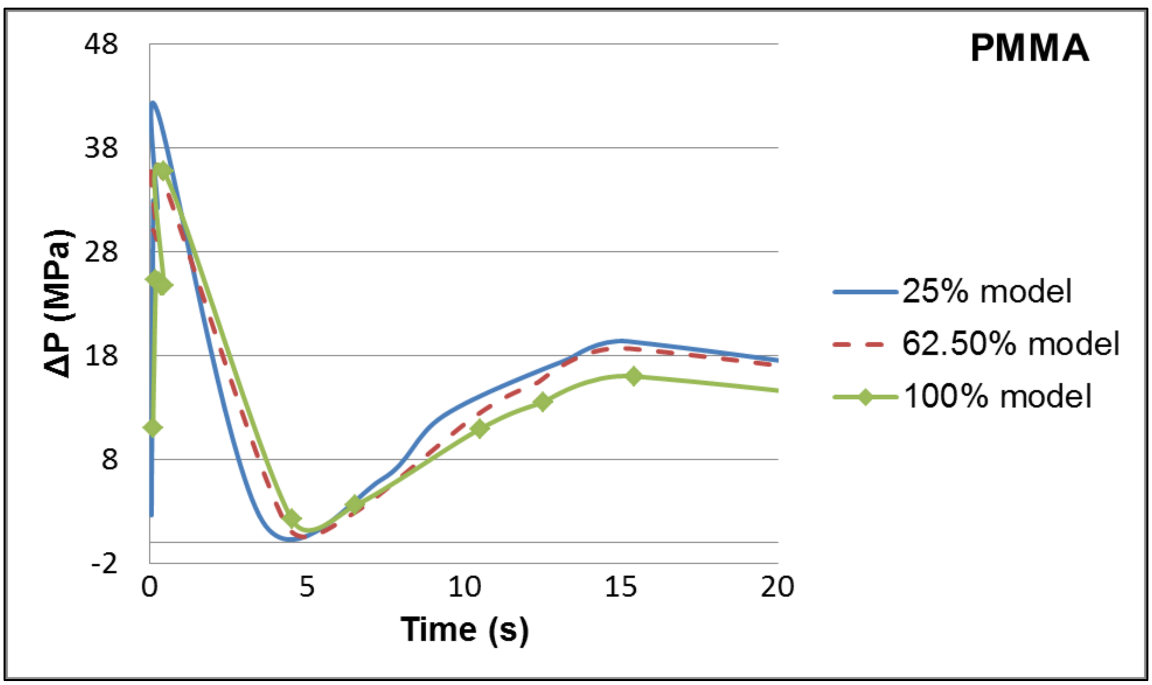


Figure 6-8: PMMA - Pressure Drop across Three Different Angles

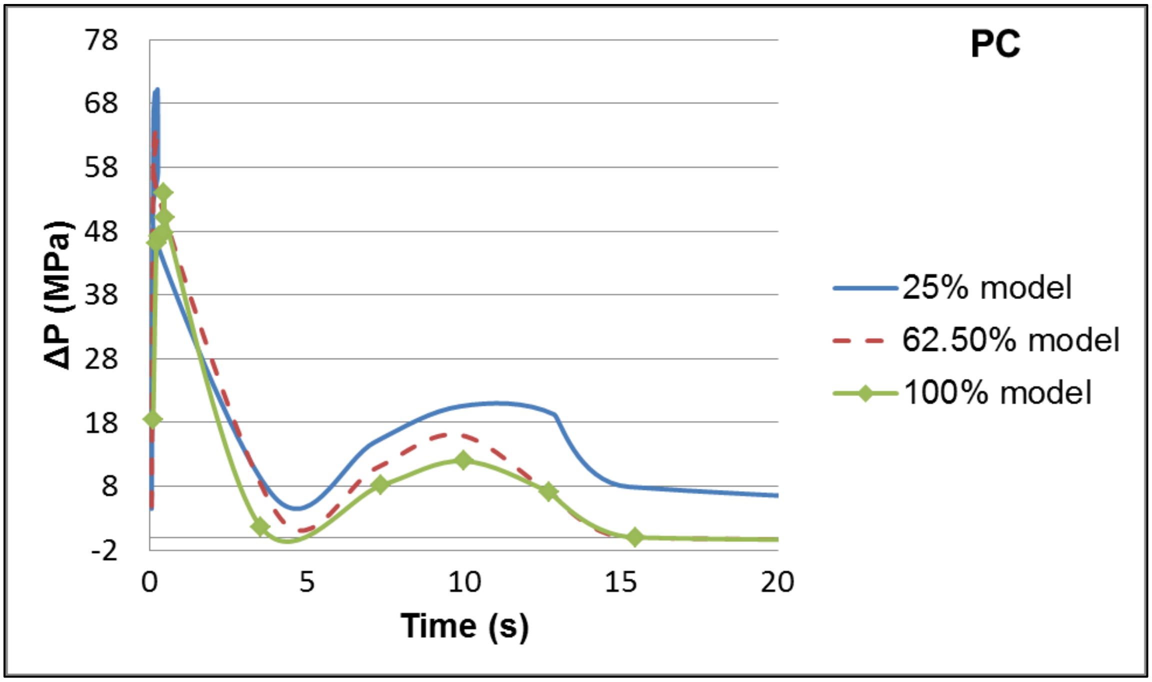


Figure 6-9: PC - Pressure Drop across Three Different Angles

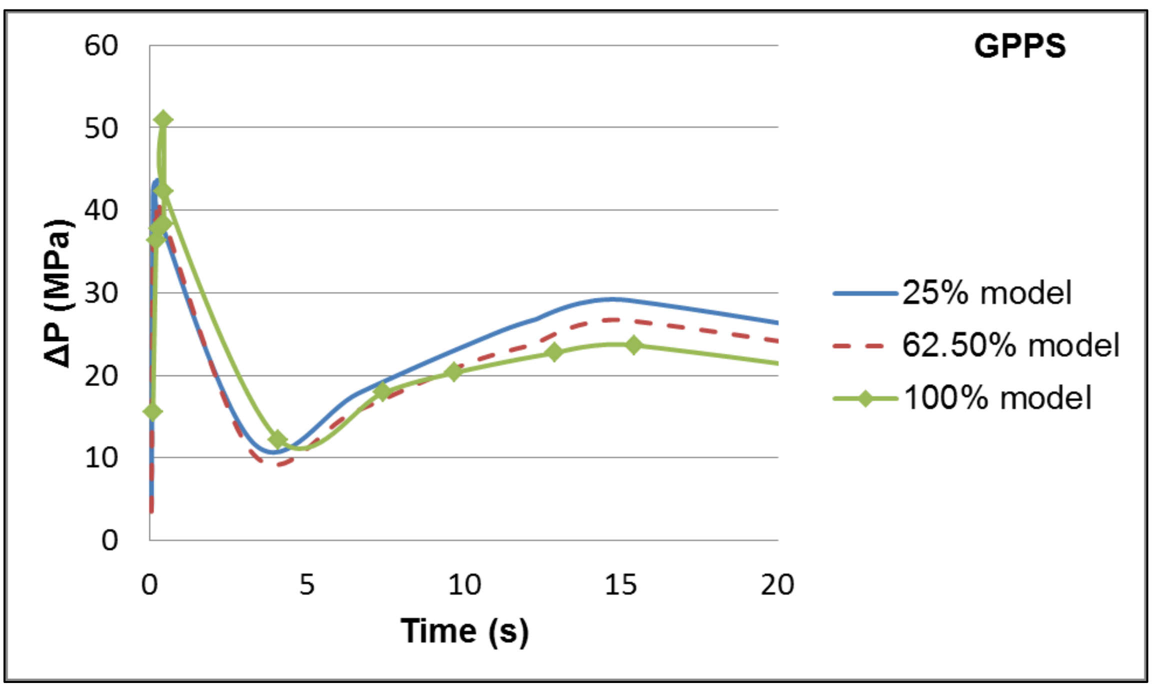


Figure 6-10: GPPS - Pressure Drop across Three Different Angles

6.4.1.3 Different Packing Pressure

The pressure drop across the valve at location 1 as a function of time was analyzed using three different packing pressures. For this analysis, the near-closed control valve position (25% model) was selected. The results for PMMA, PC and GPPS are illustrated in Figure 6-11, Figure 6-12, and Figure 6-13. According to the results, the pressure drop can be amplified by increasing the packing pressure. From the simulation results, cavity filling lasted for about 0.4 second. The lowest pressure drop is seen at a packing pressure of 55MPa (30% of the maximum pressure of the Nissei machine), followed by a packaging pressure of 82.5MPa. The simulation results were obtained from valve location 1.

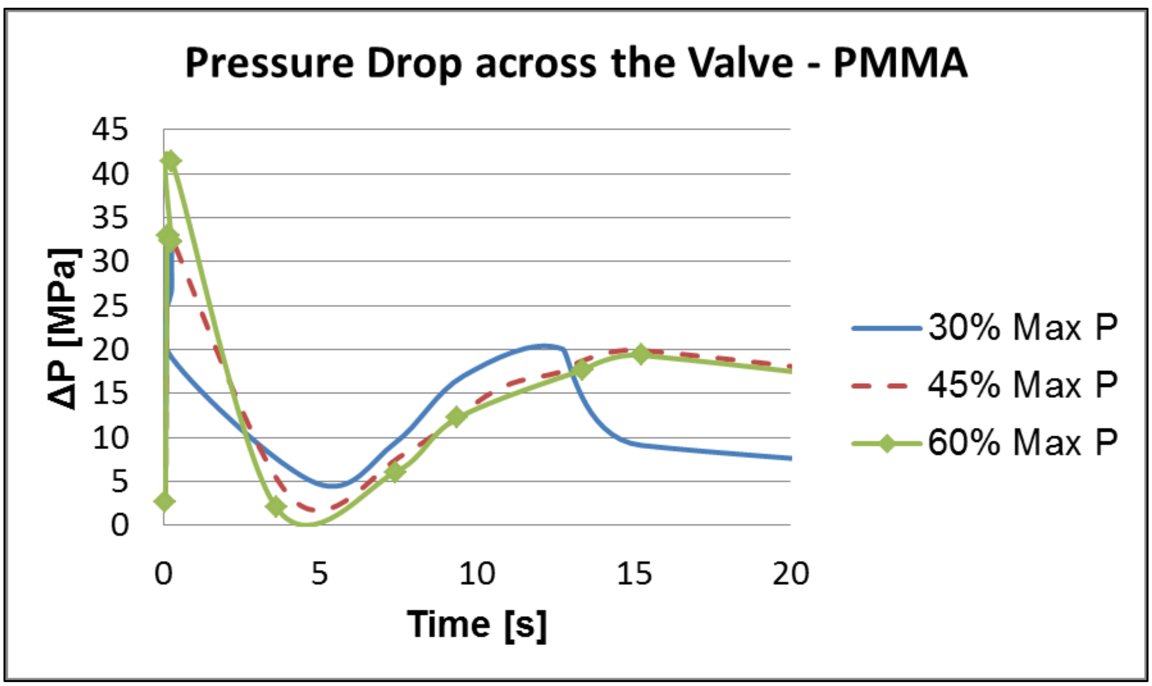


Figure 6-11: PMMA - Pressure Drop across the Valve at Two Different Levels of Packing Pressures

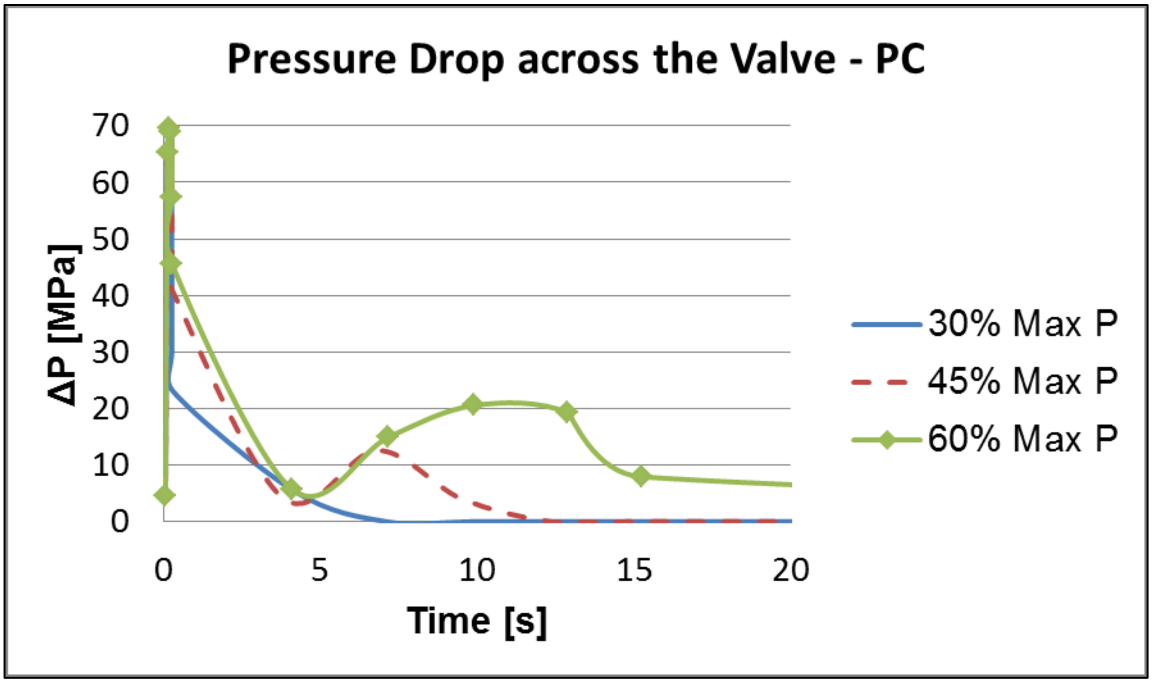


Figure 6-12: PC - Pressure Drop across the Valve at Two Different Levels of Packing Pressures

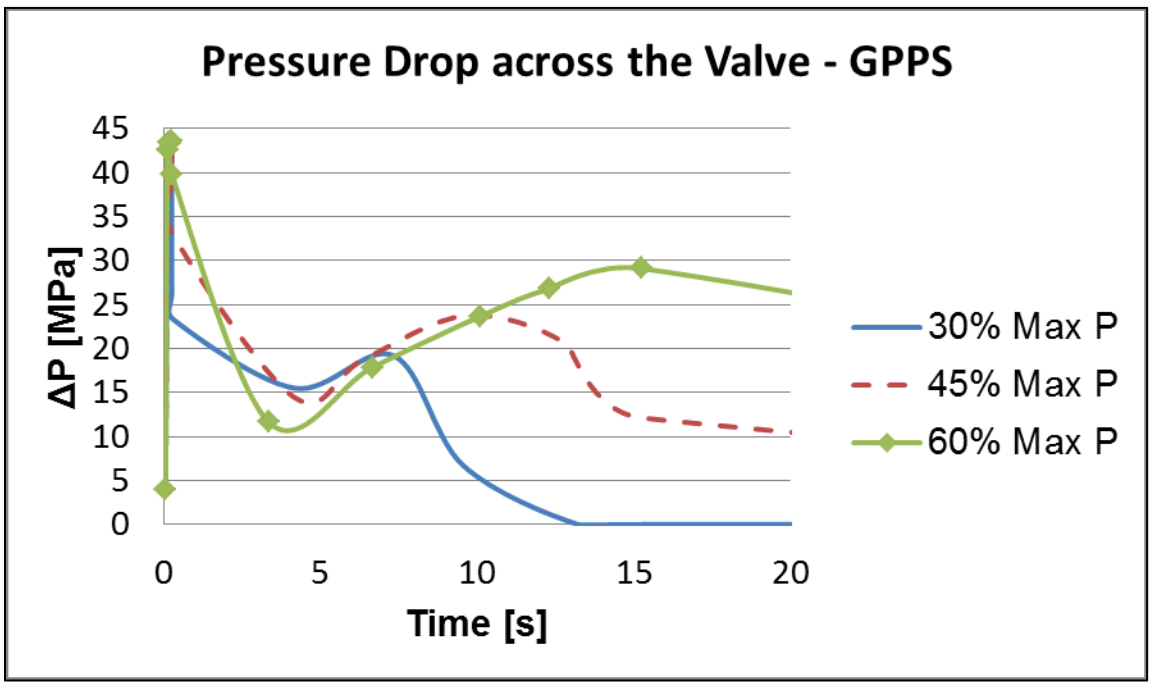


Figure 6-13: GPPS - Pressure Drop across the Valve at Two Different Levels of Packing Pressures

6.4.2 Average Volumetric Shrinkage Results

Volumetric loss (shrinkage) is the increasing percentage of volume lost from the time the packing phase ends until the part reaches ambient reference temperature. High volumetric shrinkage is a common quality problem in injection molding parts and often results in sink marks and voids. Also, non-uniform volumetric shrinkage may cause warping. The results of average volumetric shrinkage for PMMA, PC, and GPPS from this numerical simulation are were selected from node 3.

6.4.2.1 Different Valve Locations

The numerical simulation was performed at two different packing pressures, 30% and 60% of the machines' maximum packing pressure. STYRON® 685D (GPPS) material was selected for the multi-valve location analysis and the control valve was set at the near closed-position (θ_3 = 67.5°). The results of the 30% and 60% of maximum pressure can be seen Figure 6-16 and Figure 6-15 respectively.

According to results, the volume shrinkage had a very small variation (less than 1%) within all four locations. When the packing pressure was set to 30% of the maximum packing pressure, as illustrated in Figure 6-16, locations 1 showed volume shrinkage of 6%, which is the highest recorded. Location 2 had the lowest volume shrinkage of 5.55%. The difference between the highest and lowest volume shrinkage is less than 0.5%, which is very small.

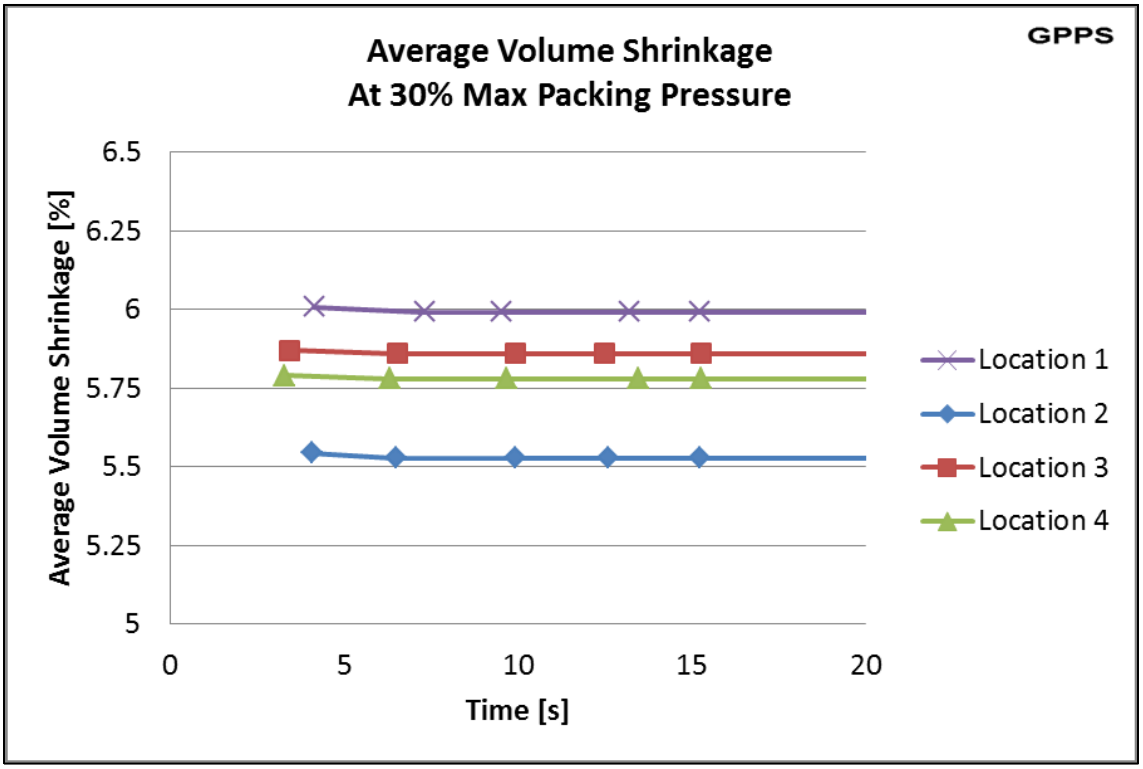


Figure 6-14: GPPS-Average Volume Shrinkage at different Locations (30% max packing pressure)

When the packing pressure was doubled to 60% of the maximum pressure, as shown in Figure 6-15, the average volume shrinkage was nearly cut in half. Location 1 initially had the highest volume shrinkage, but it was reduced from 3.4% to 3% at the end of the packing cycle. Location 2 still showed the lowest final volume shrinkage of 2.75%. However, since the difference is less than 0.25%, other factors must be taken into consideration prior to selecting the best valve location.

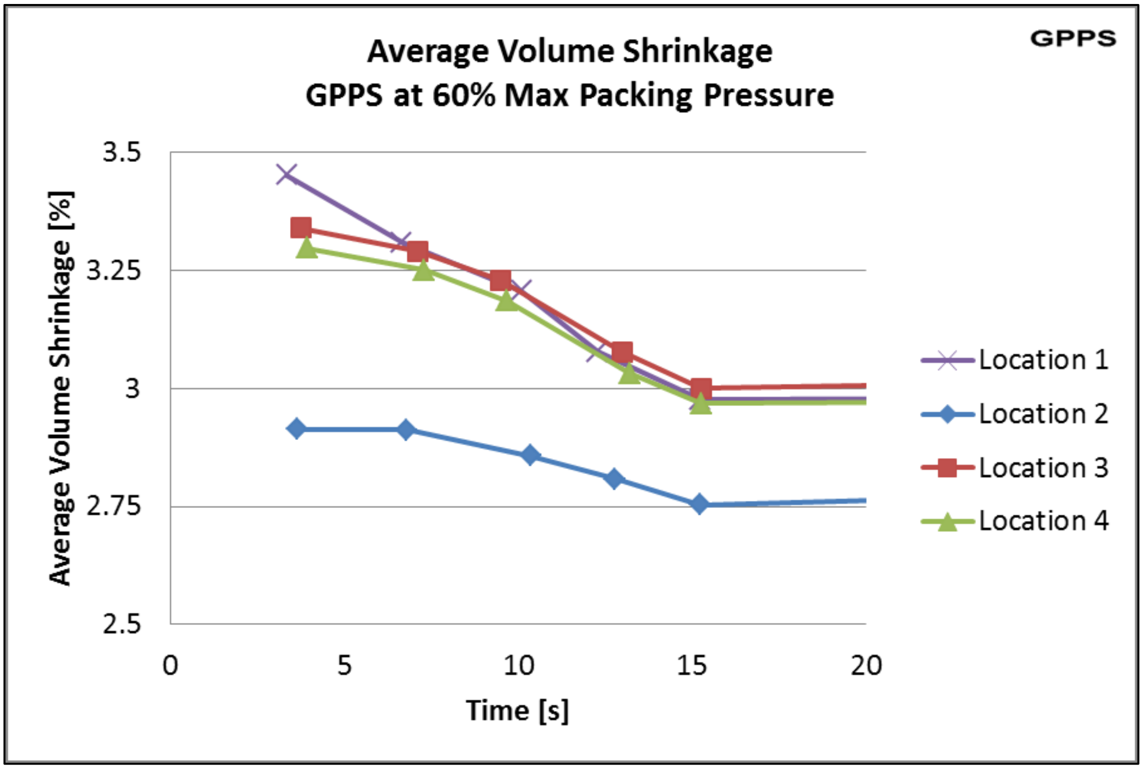


Figure 6-15: GPPS- Average Volume Shrinkage at different Locations (60% max packing pressure)

6.4.2.2 Different Valve Angles

Any change in the control valve angle that leads to restrictions in melt flow or packing pressure has an impact on the final shrinkage of the injection molded product. Results showing the average volume shrinkage of three different valve angles at node 3 as a function of the valve angle at the end of packing phase are illustrated in Figure 6-16, Figure 6-17, and Figure 6-18. This numerical simulation was performed on PMMA, PC and GPPS at three different packing pressures (30%, 45% and 60% of the machines' maximum packing pressure). All results were obtained from valve location 1.

According to the results obtained from Moldflow, there is a direct relationship between volume shrinkage and valve angle. Restricting melt flow and packing pressure increases the average volume shrinkage on the part. Also, changing the packing processing parameters can impact the volume shrinkage.

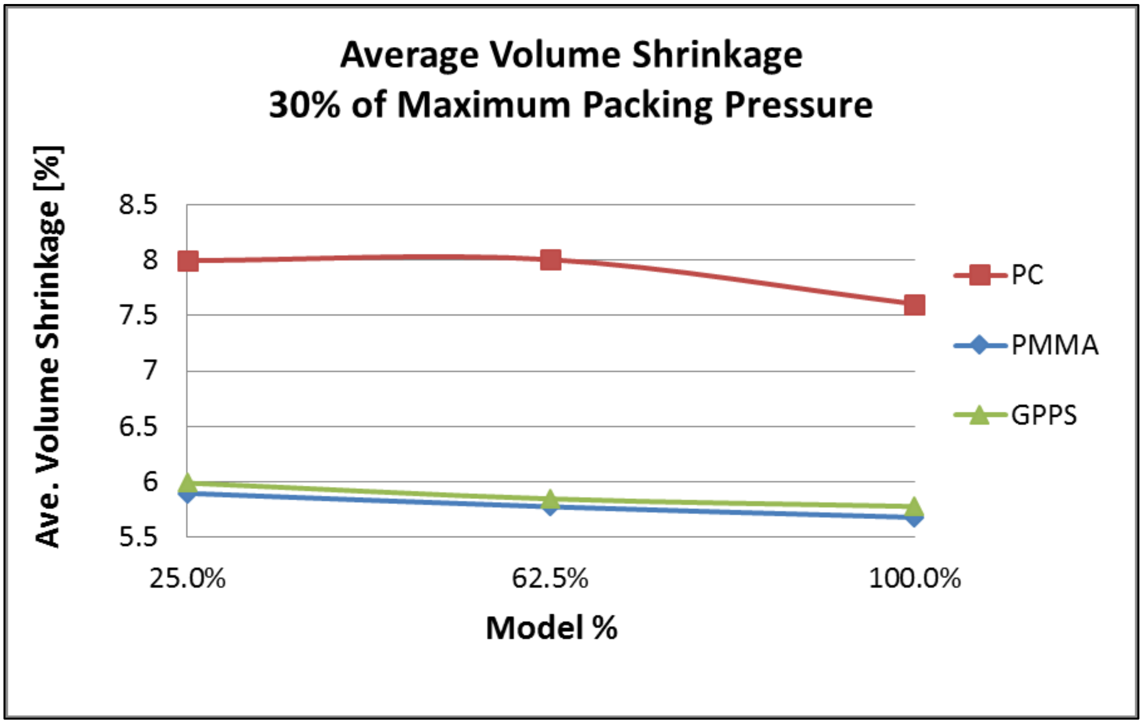


Figure 6-16: Average Volume Shrinkage Results at Node 3 vs. Model % (Valve Angle)

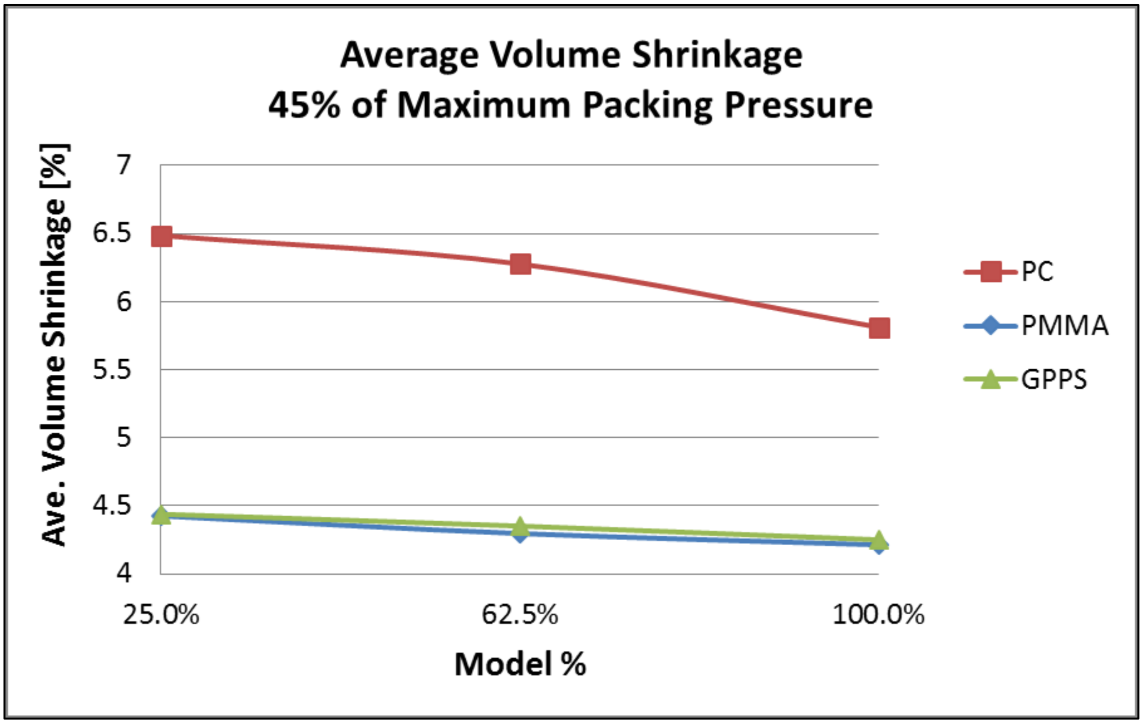


Figure 6-17: Average Volume Shrinkage Results at Node 3 vs. Model % (Valve Angle)

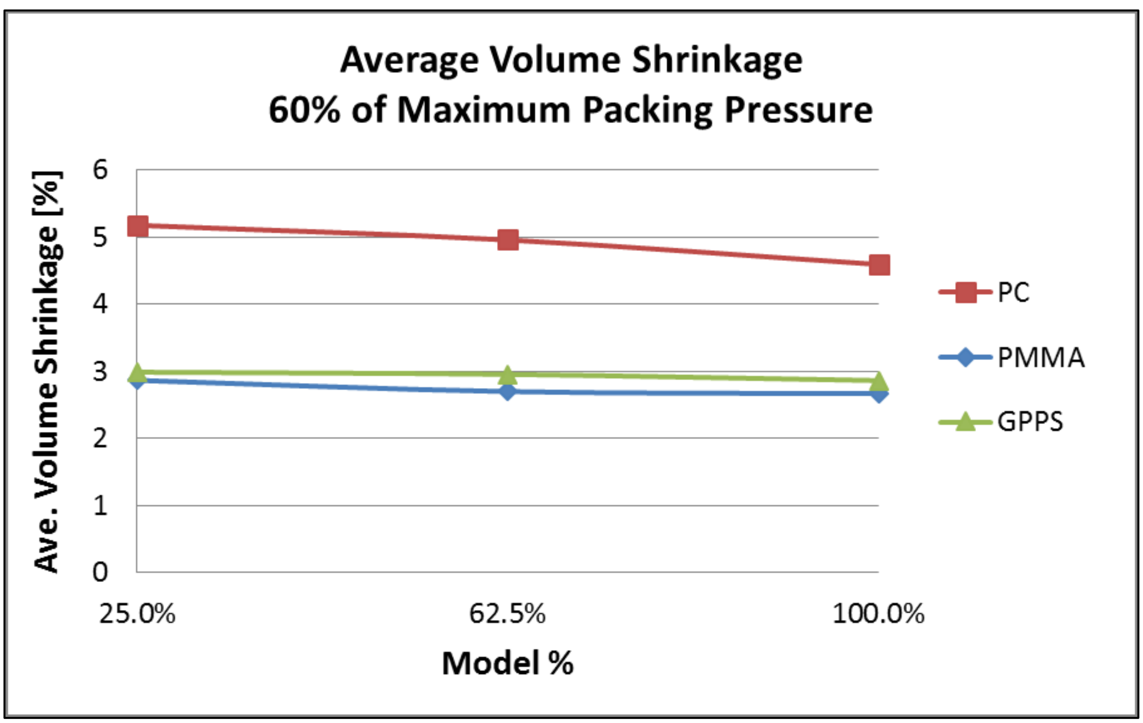


Figure 6-18: Average Volume Shrinkage Results at Node 3 vs. Model % (Valve Angle)

6.4.2.3 Different Packing Pressure

Another variable that can affect volume shrinkage is packing pressure. The results of the average volume shrinkage for all three different valve angles at node 3, as a function of packing pressure at the end of packing phase are shown in Figure 6-19, Figure 6-20, and Figure 6-21. The numerical simulation was performed for PMMA, PC and GPPS at three different valve angles (25%, 62.5% and 100% models). The results were also obtained from valve location 1.

The results show an inverse relationship between average volume shrinkage and packing pressure. When keeping the valve angle constant, the average volume shrinkage was reduced as a result of increasing the packing pressure.

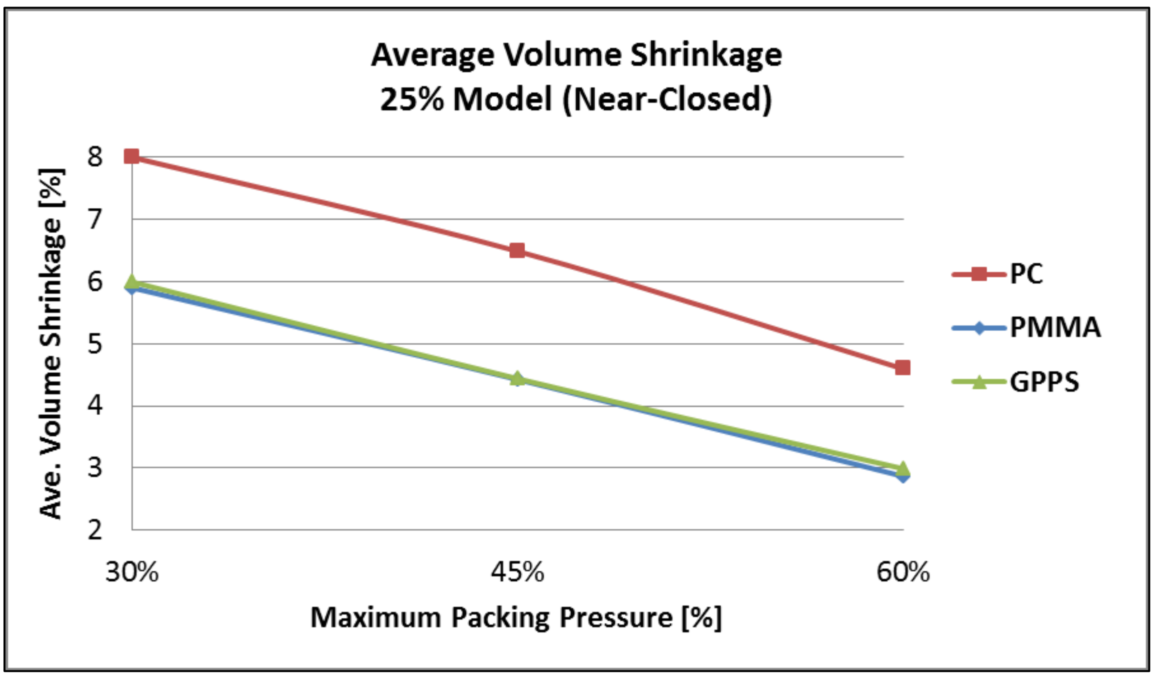


Figure 6-19: Average Volume Shrinkage Results at Node 3 vs. Packing Pressure

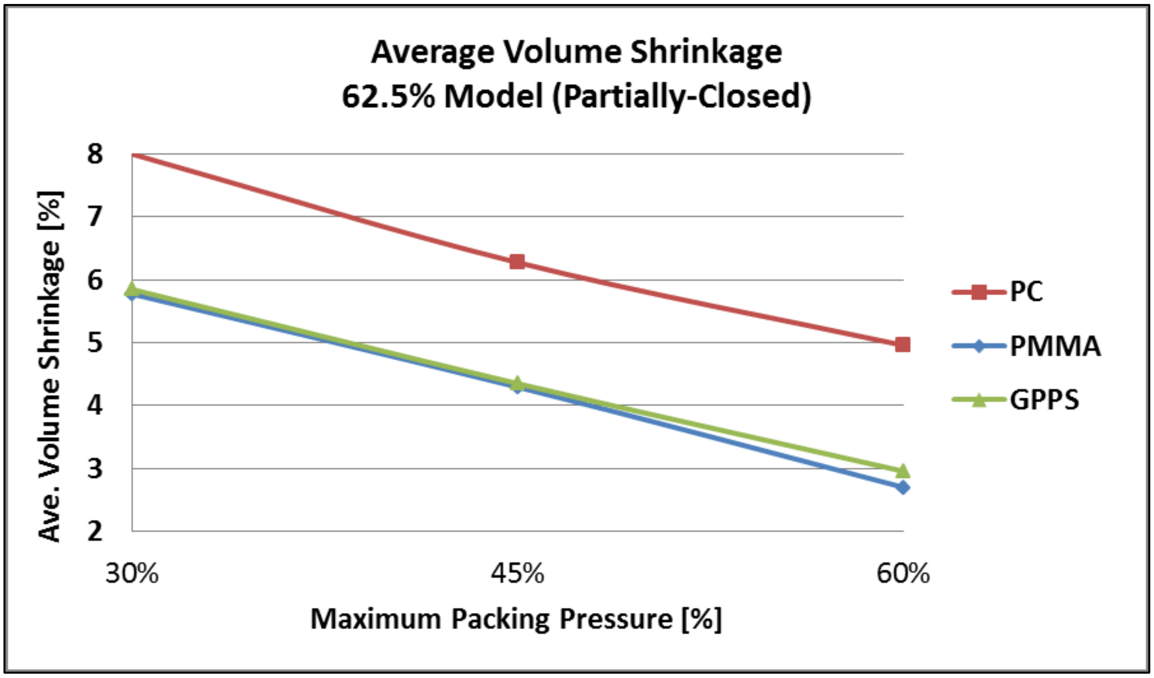


Figure 6-20: Average Volume Shrinkage Results at Node 3 vs. Packing Pressure

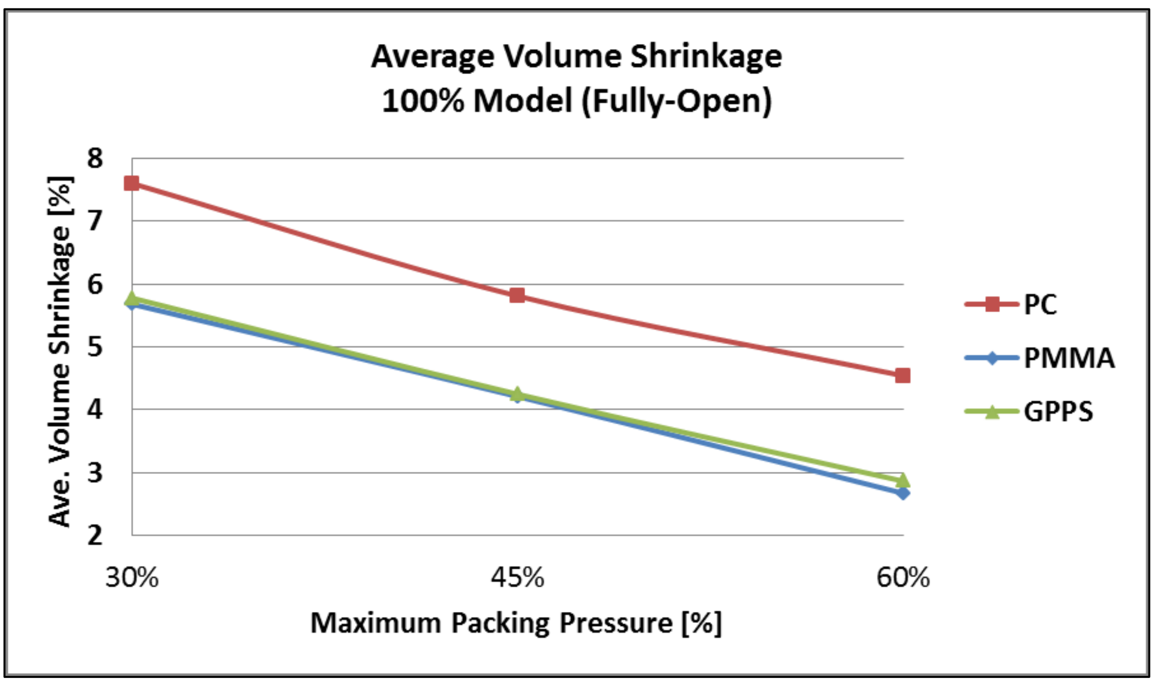


Figure 6-21: Average Volume Shrinkage Results at Node 3 vs. Packing Pressure

6.4.3 Deflection Results

The deflection results were obtained from three different numerical simulations. The first simulation examines maximum deflection at four different valve locations. The second simulation evaluates the impact of changing the valve angle at constant packing pressure on both the deflection of each node and the maximum deflection. The final simulation assesses the relationship between packing pressures on the warpage of the final part.

Total deflection results have been selected from three different positions: node 1, node 2, and node 3 positioned at 13.63 mm, 57.64 mm, and 100.52 mm away from the gate in an axial direction, respectively. Maximum deflection results have been obtained from node 3 only.

6.4.3.1 Different Valve Locations

This analysis was performed using only GPPS material and a control valve angle of 67.5º (25% model). The simulations were completed for all four valve locations at 30% and 60% of maximum packing pressure. The maximum deflection results are shown in Figure 6-22 and Figure 6-23, and they represent the maximum value of warpage or deflection at node 3 over time. It can be seen that as the packing pressure increases, maximum deflection (warpage) is decreased. Location 1 shows the least warpage followed by location 4. Location 2 leads to the highest warpage on the final part.

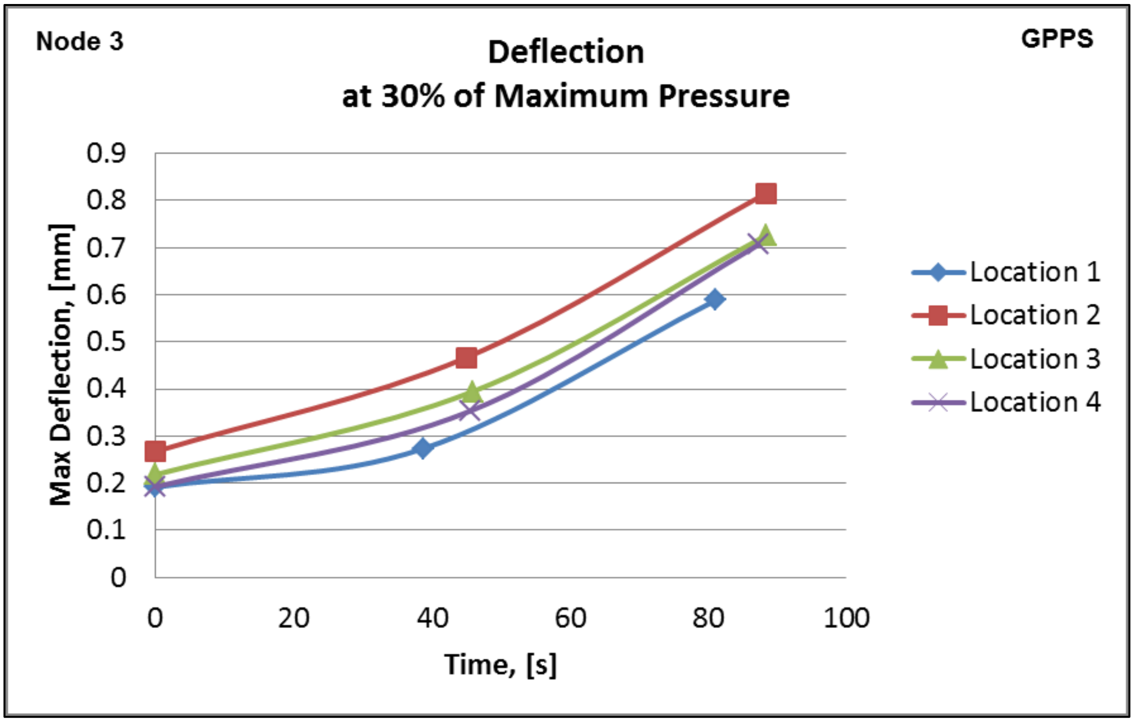


Figure 6-22: Maximum Deflection - Different Valve Locations, 30% Max Packing Pressure (GPPS)

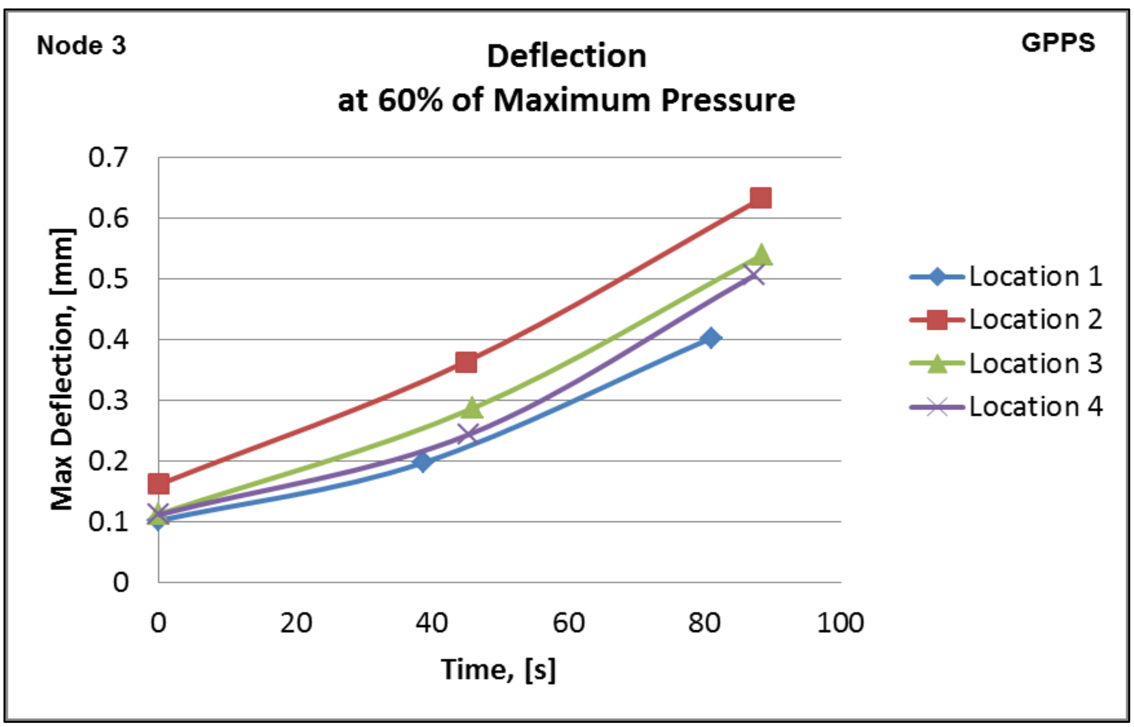


Figure 6-23: Maximum Deflection - Different Valve Locations, 60% Max Packing Pressure (GPPS)

6.4.3.2 Different Valve Angles

Two numerical simulations have been performed on three clear polymers at valve location 1. The objective of the first analysis was to study the impact of turning the control valve at constant packing pressure (110MPa) on the deflection of each node. The deflection results of PMMA, PC, and GPPS are presented as the warpage in each of the three nodes, and they are shown in Figure 6-24, Figure 6-25, and Figure 6-26. It can be seen that as the control valve angle is increased, the total deflection (warpage) is reduced. Having the control valve at the near close position (θ = 67.5º, 25% model) shows the least deflection or warpage.

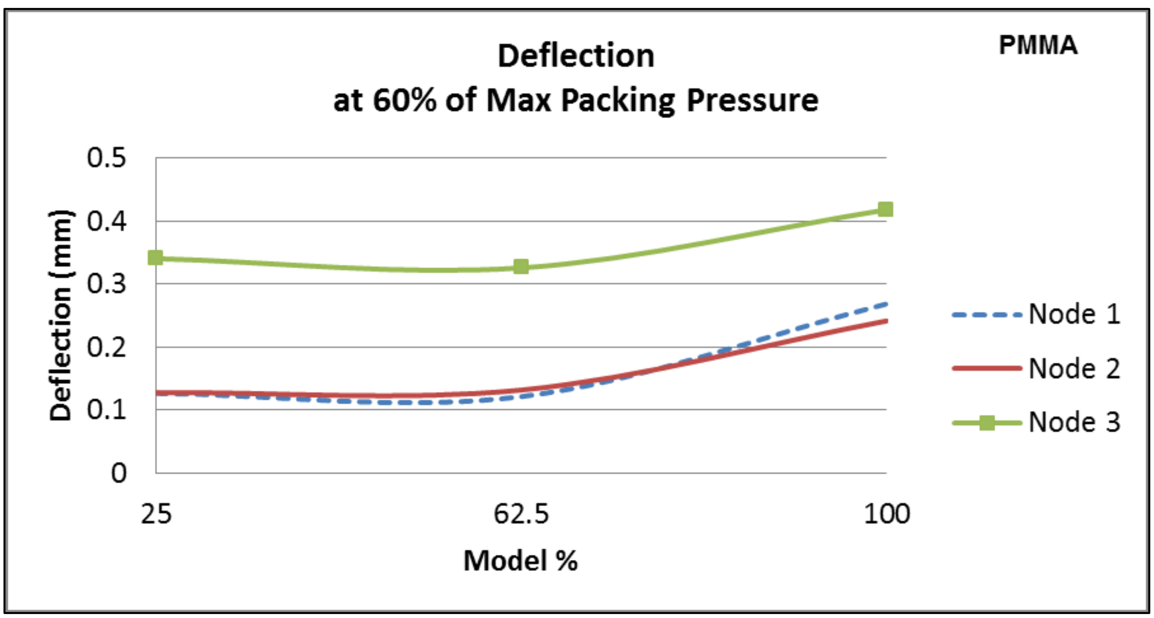


Figure 6-24: Deflection - Different Valve Positions at 110MPa (PMMA)

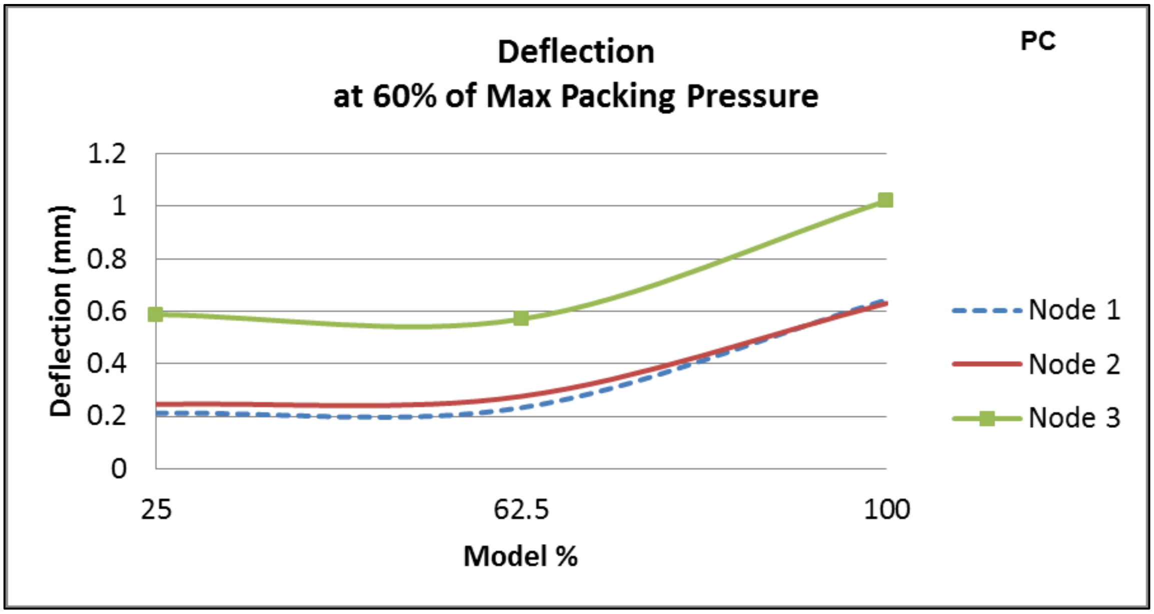


Figure 6-25: Deflection - Different Valve Positions at 110MPa (PC)

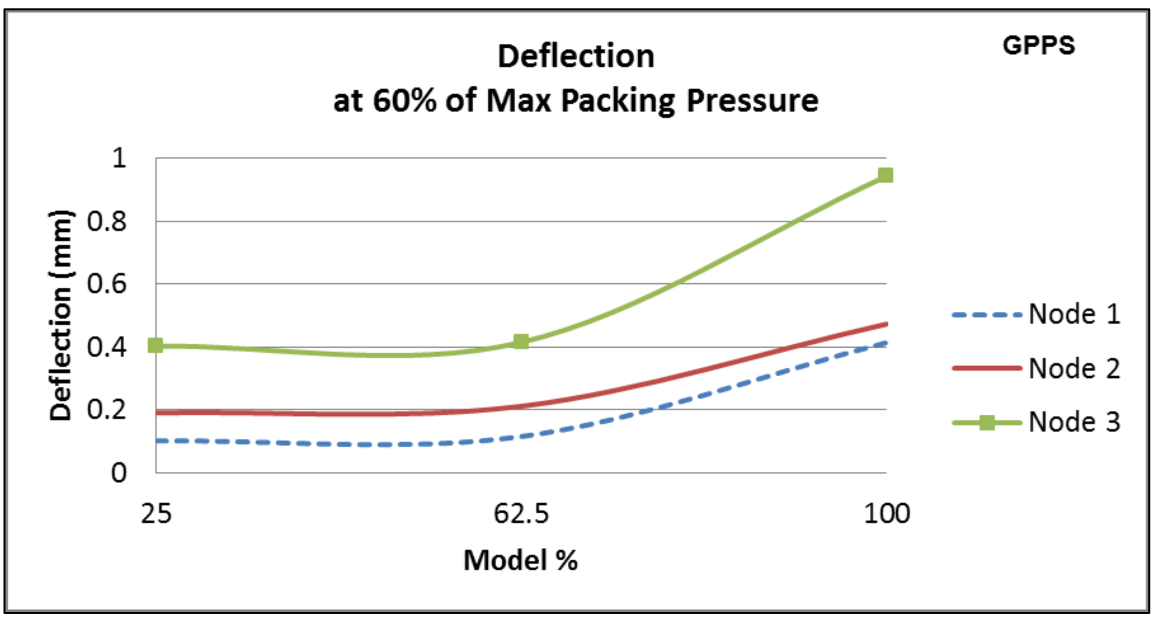


Figure 6-26: Deflection - Different Valve Positions at 110MPa (GPPS)

In the second simulation, the focus is only on the maximum warpage (deflection at node 3) with respect to changing the valve angle at three different constant packing pressures. The simulation results were also based on valve location 1. The maximum deflection results of PMMA, PC, and GPPS are illustrated in Figure 6-27, Figure 6-28, and Figure 6-29. The results show that having the valve at the fully open position (100% model) produces the highest warpage. The near close position (25% model) shows the least deflection or warpage.

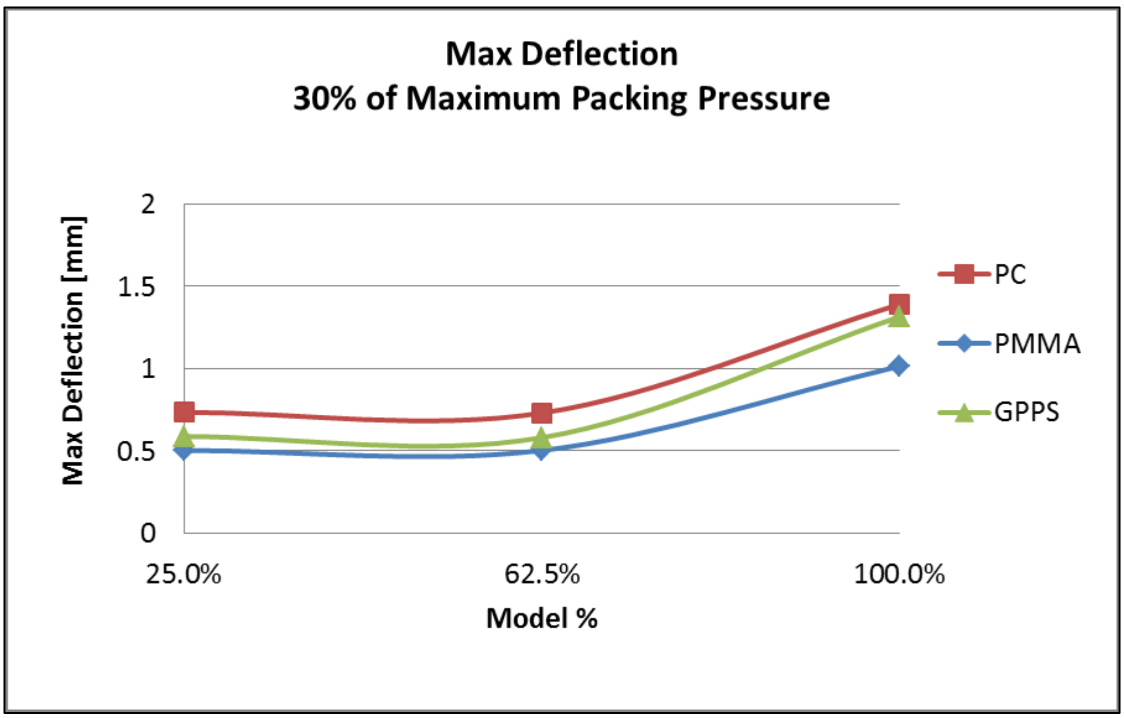


Figure 6-27: Maximum Deflection at Different Valve Positions (30% of Max Packing Pressure)

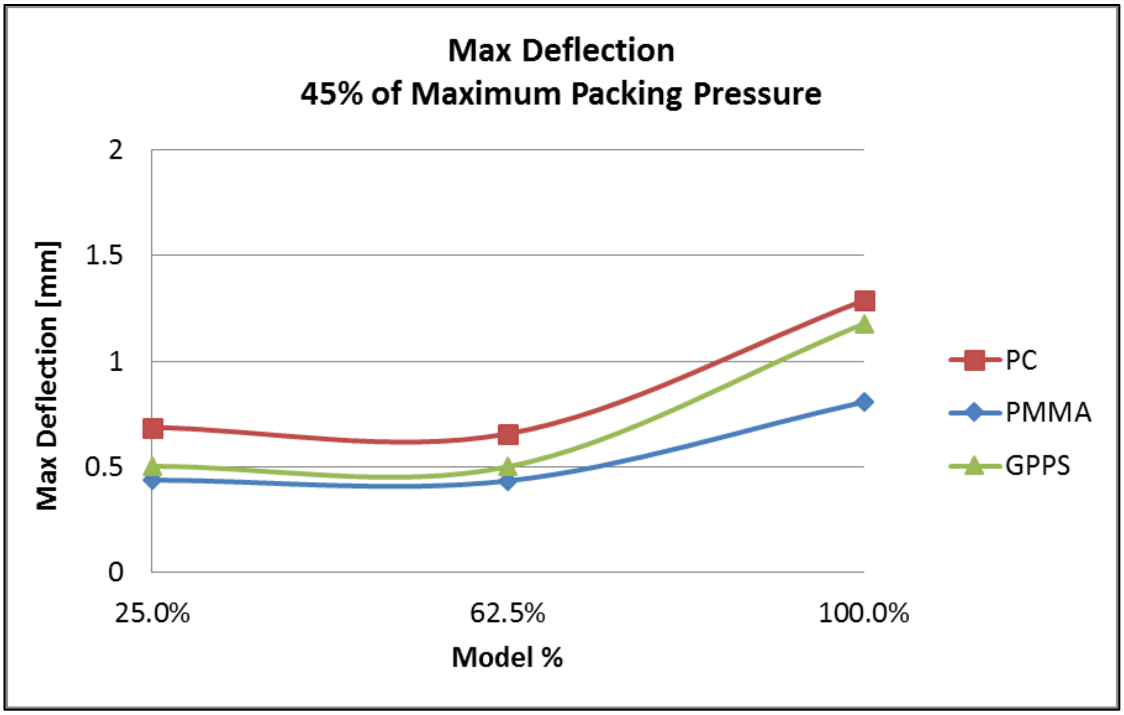


Figure 6-28: Maximum Deflection at Different Valve Positions (45% of Max Packing Pressure)

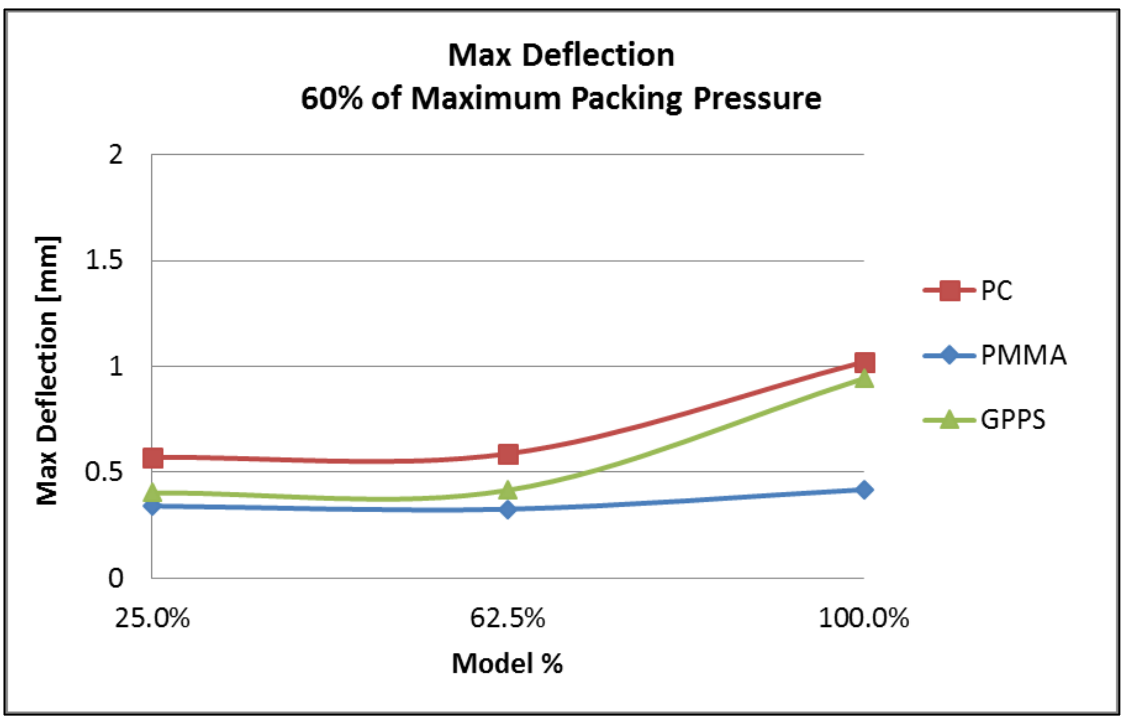


Figure 6-29: Maximum Deflection at Different Valve Positions (60% of Max Packing Pressure)

6.4.2.3 Different Packing Pressure

This analysis focusses on studying the effect of changing the packing pressure on the deflection of node 3 (maximum warpage) of PMMA, PC, and GPPS materials at a constant valve angle and valve location 1. The results showing the influence of packing pressure on maximum deflection at fixed valve position are presented in Figure 6-30, Figure 6-31, and Figure 6-32. The results show that as the packing pressure increases, the maximum deflection (warpage) is reduced.

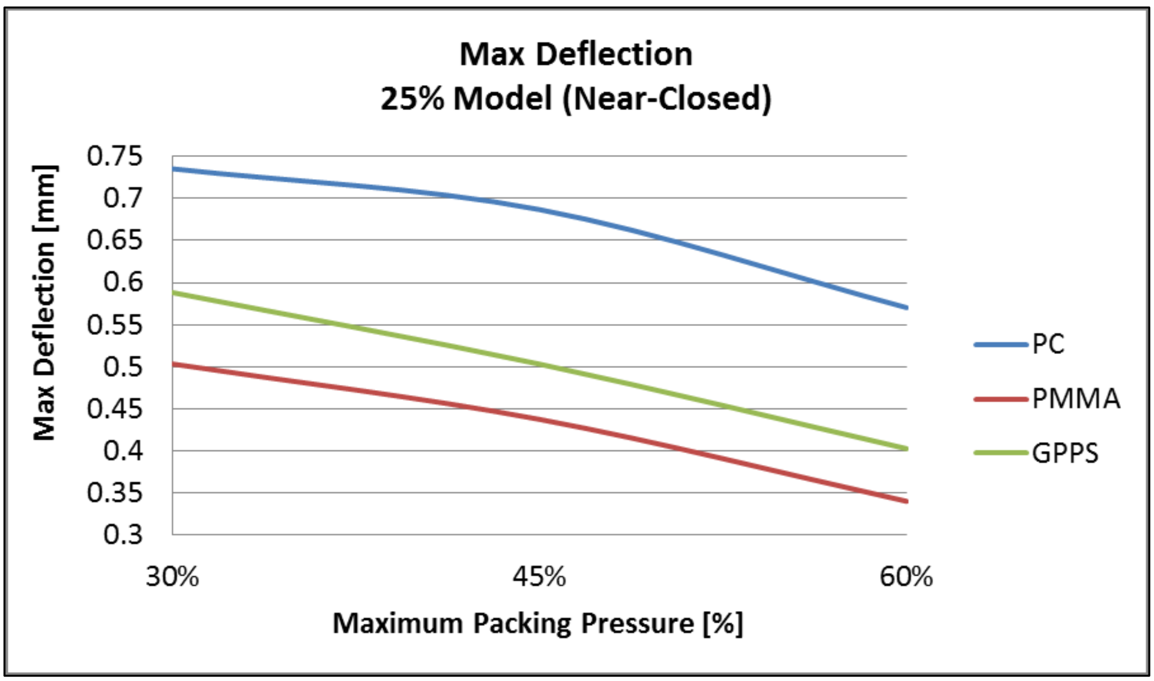


Figure 6-30: Maximum Deflection at Different Packing Pressure (25% Model)

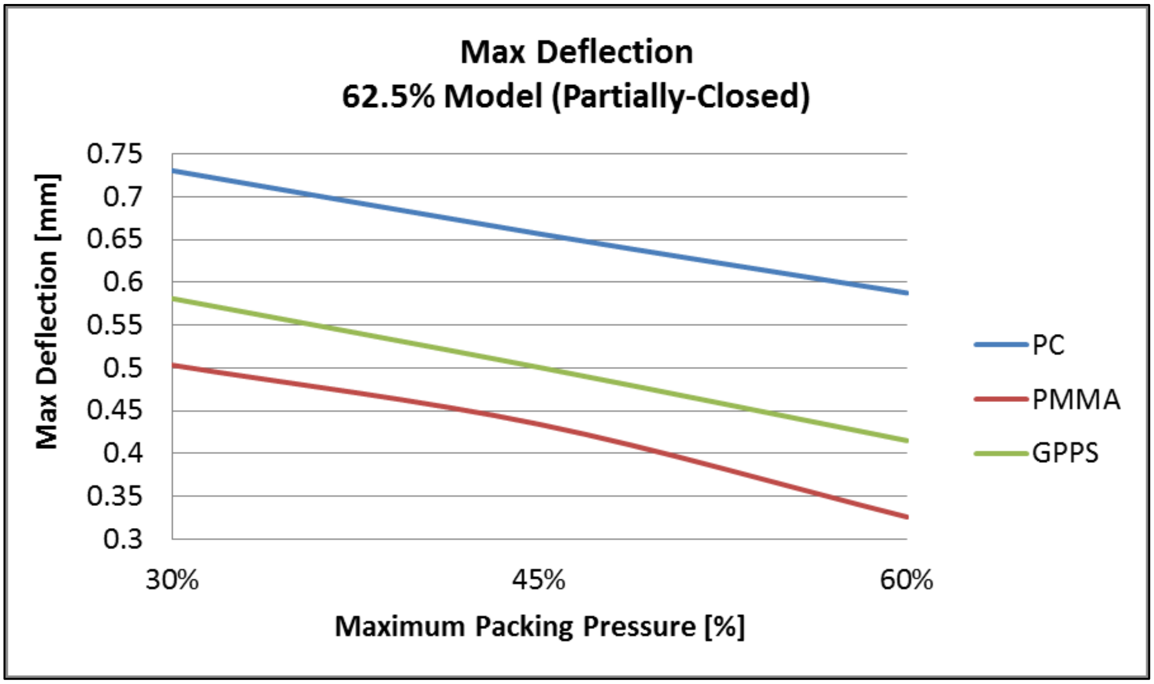


Figure 6-31: Maximum Deflection at Different Packing Pressure (62.5% Model)

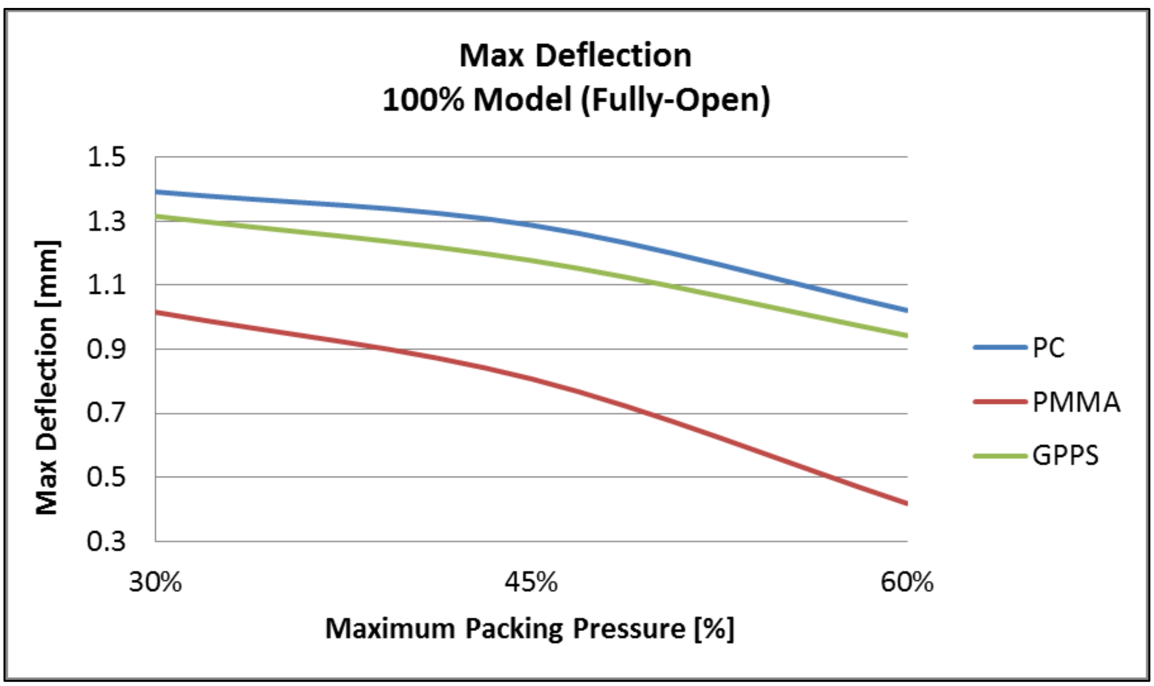


Figure 6-32: Maximum Deflection at Different Packing Pressure (100% Model)

6.4.4 *Shear Rate*

The shear rate of PMMA, PC, and GPPS materials at a valve location 1 and at different packing pressure and valve angles have been analyzed and summarized in Table 6-4. According to the results, the highest shear rates were observed when the valve is near closed position with 110MPa packing pressure.

Table 6-4: Shear Rate of PMMA, PC and GPPS at different Valve Angles and Packing Pressure

	30% Packing Pressure			45% Packing Pressure			60% Packing Pressure		
Valve Position	**PMMA**	**PC**	**GPPS**	**PMMA**	**PC**	**GPPS**	**PMMA**	**PC**	**GPPS**
100%	4461	3631	3484	7012	3925	3673	11022	4536	4425
62.5%	14067	15745	13065	18650	17090	14319	19229	14504	14112
25%	19773	19850	17174	20176	20580	18062	22237	23225	19019

The shear rate results of the three clear polymers were sufficiently close enough to each other. The maximum shear rate contours of PMMA, PC, and GPPS using the 25% valve model and 60% of the machine's maximum packing pressure are shown in Figure 6-33, Figure 6-34, and Figure 6-35 respectively. The maximum shear rate results were slightly higher than 20,000 1/sec for PMMA and PC materials.

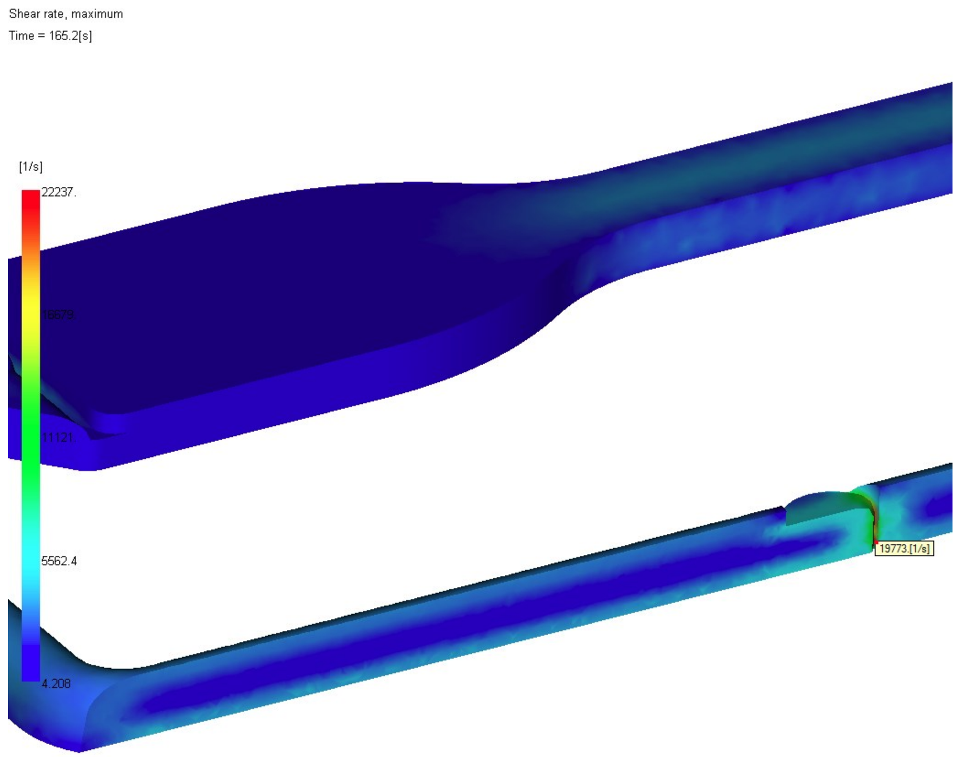


Figure 6-33: Shear Rate Contours – PMMA at 60% of Maximum Packing Pressure (25% Model)

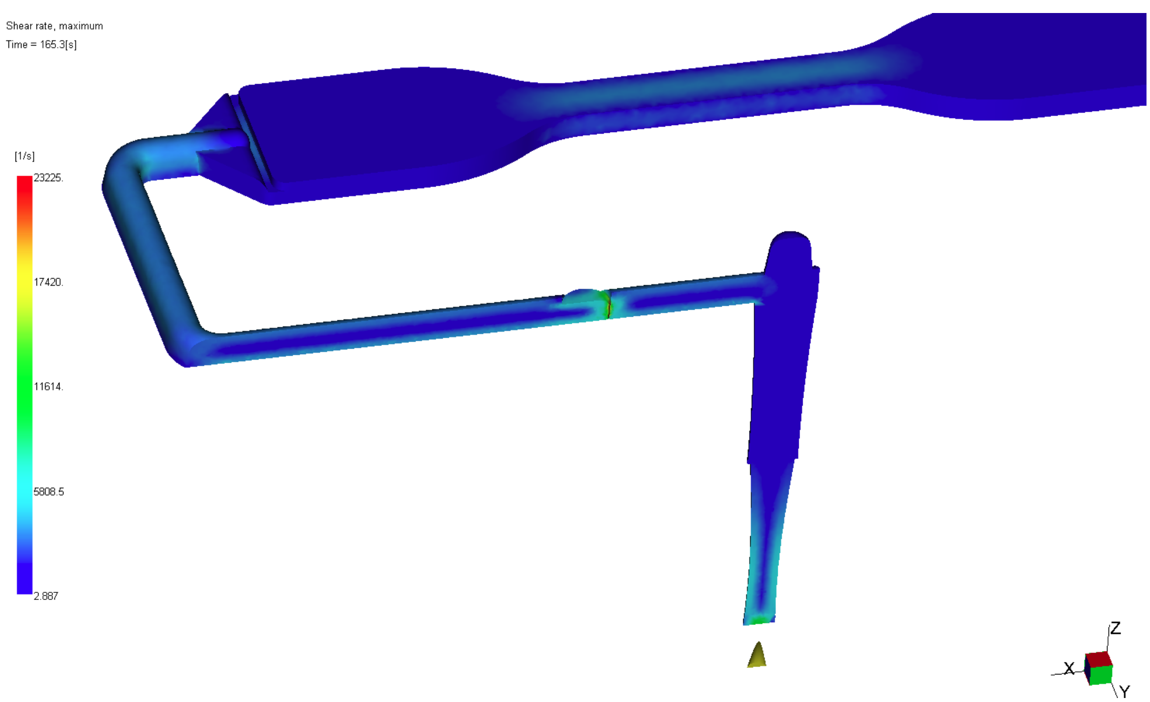


Figure 6-34: Shear Rate Contours – PC at 60% of Maximum Packing Pressure (25% Model)

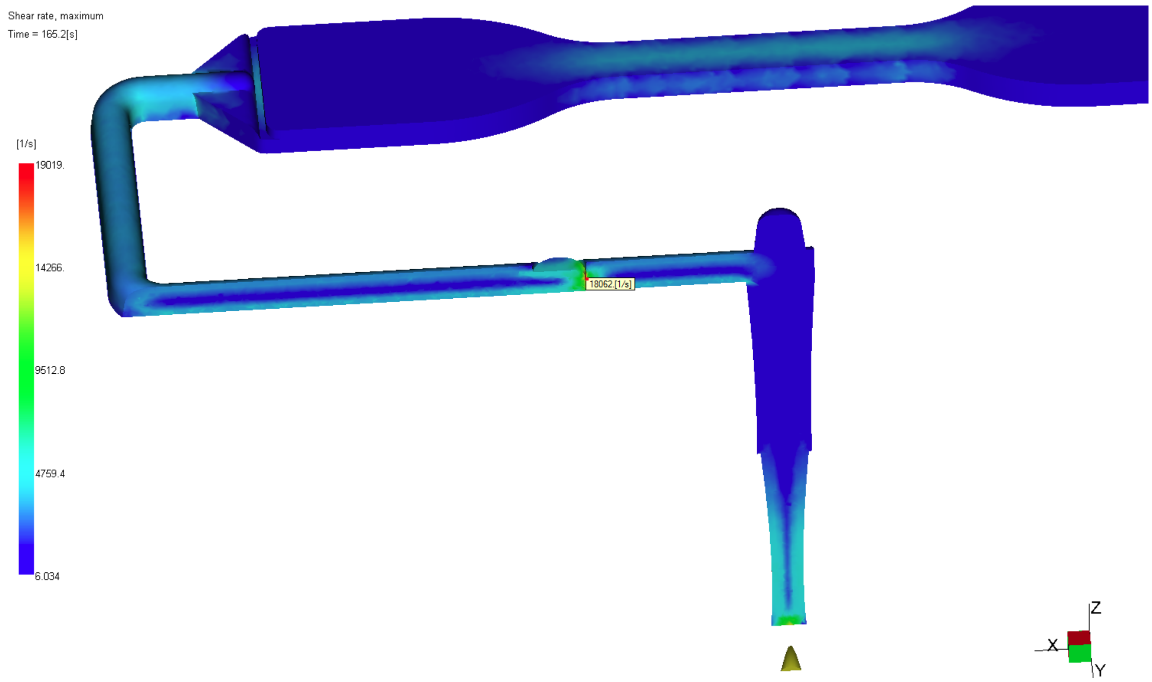


Figure 6-35: Shear Rate Contours – GPPS at 60% of Maximum Packing Pressure (25% Model)

High shear rate can cause material degradation, especially if additives have been added. Since no additives were included, the desired shear rate target was under 40,000 1/sec for all of the three materials. The highest shear rate recorded was 23,225 1/sec for Polycarbonate material. Lower injection and packing pressures usually produce lower shear rate and shear stress levels. If additives were added and the desired shear rate dropped below 20,000 1/sec for all three materials, either the packing pressure has to be decreased or the injection time must be increased to reduce the shear rate.

The simulation results of the shear rates as a function of valve angle at 55MPa and 110MPa constant pressures are shown in Figure 6-36 and Figure 6-37 respectively.

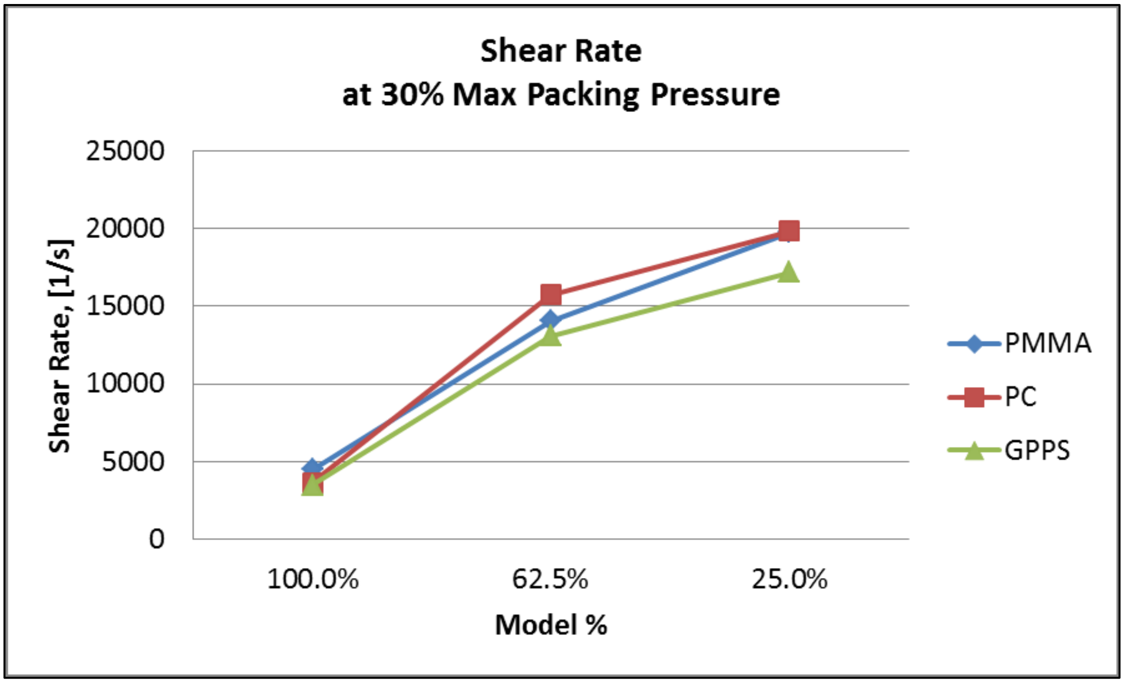


Figure 6-36: Shear Rate vs. Valve Angle at 30% of Maximum Packing Pressure

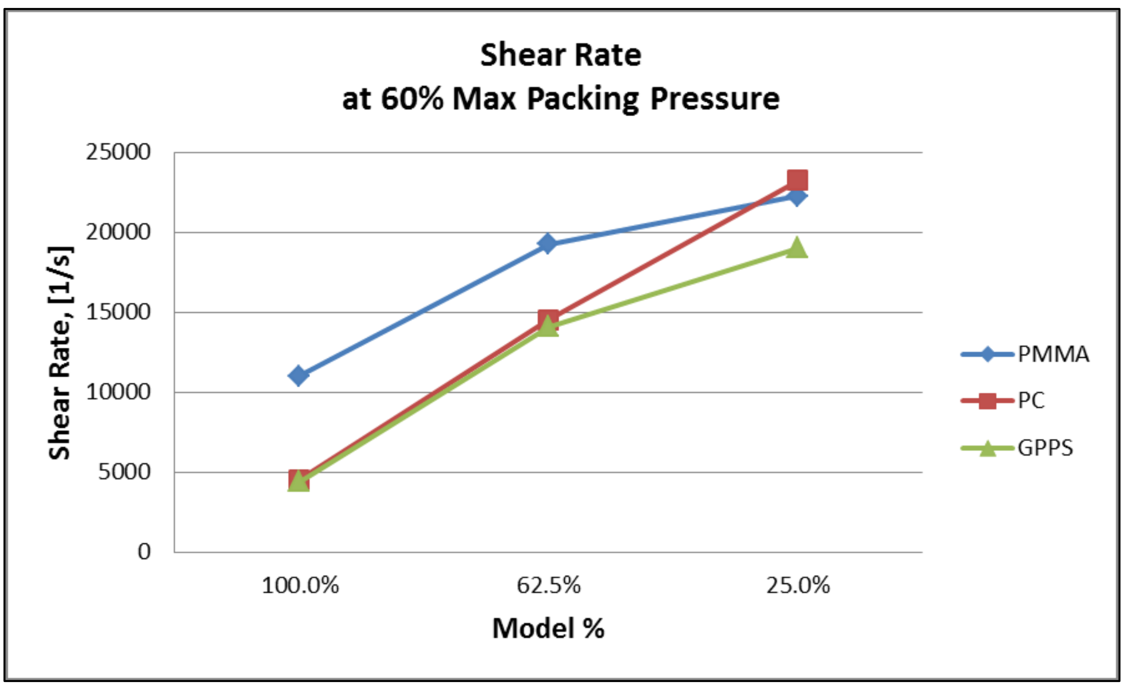


Figure 6-37: Shear Rate vs. Valve Angle at 60% of Maximum Packing Pressure

The results of the shear rate as a function of maximum packing pressure is presented in Figure 6-38.

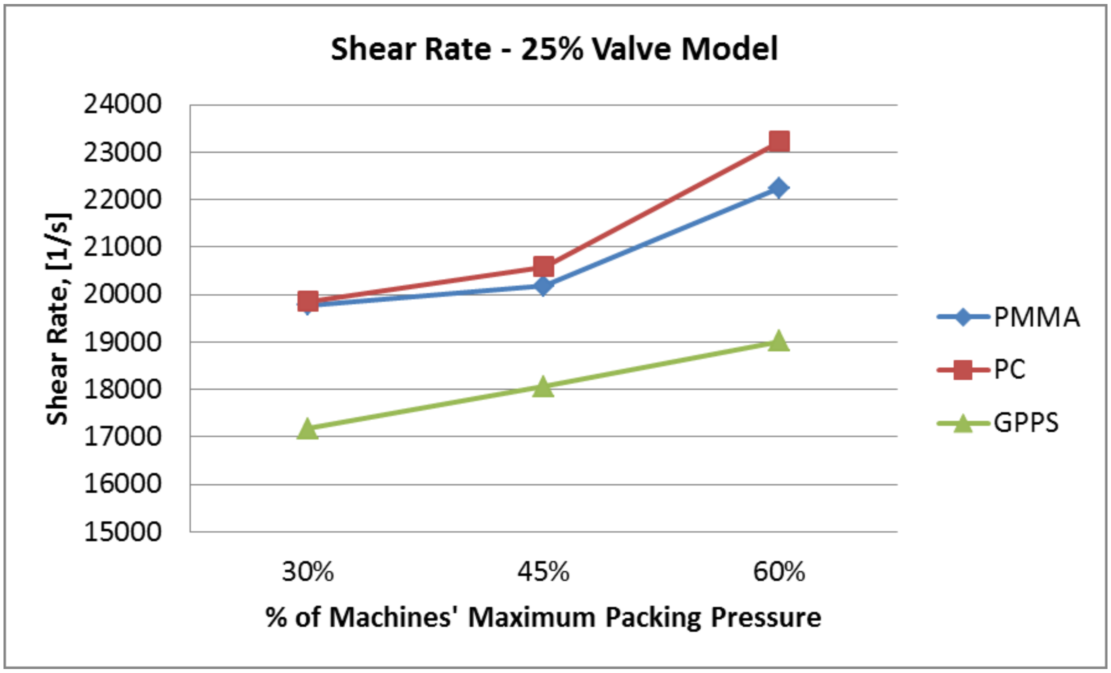


Figure 6-38: Shear Rate vs. Packing Pressure (25% Model)

The next chapter details the experimental results of the effect of different packing processing conditions on optical quality and part physical strength. It also demonstrate the impact of the melt modulation technique on the geometrical quality of the injection molded part and its birefringence.

CHAPTER 7 – EXPERIMENTAL RESULTS

In order to demonstrate the effectiveness of melt modulation control on product optical and physical properties, a series of experiments have been conducted.

7.1 Introduction

The melt modulation technique has been implemented to control the packing parameters and to determine optical quality in terms of both precision of geometric dimensions and optical birefringence. These results have helped expand current melt modulation capabilities to enhance optical properties of clear polymers in cold runner based injection molding. The primary goal of the experiments was to investigate the processing parameters and their impact on the properties of injection-molded products and to validate the use of the melt modulation system.

This chapter details the results of two experiments. The first experiment showed results of the effect of different packing processing conditions on optical quality and part strength. The second experiment test demonstrated the impact of the melt modulation technique on the geometrical quality of the injection molded part and its birefringence.

7.2 Materials

The same clear polymers used in chapter 6 were selected for the experiments; Polymethyl Methacrylate Plexiglas® V-920 (PMMA), Polycarbonate LEXAN™ 101-111 (PC), and STYRON® 685D (GPPS).

The test specimens used to for the first set of experiments were dog-bone shaped standard tensile test specimens (ASTM D638 – Type I). The geometry and dimensions of test specimens is presented in Figure 5-1.

The second set of experiments incorporates the modular melt modulation system. Since the size of the mold insert was smaller, ASTM D638 – Type IV dog-bone shaped test specimens were selected for testing. Type VI test specimens have similar geometry to type I but are smaller. The geometry and dimension of the specimens used are identical to Figure 6-1 but without gates. Since the melt modulation valves were incorporated, the control valves replace the need for gates.

7.3 Experimental Results

A series of experimental were performed to investigate the effect of the melt modulation technique on cold runner injection molding parts. The injection molding machine used to conduct the experiment was a Nissei model PS40E5ASE, and the machine's specifications summarized in Table 5-2. The injection molding machine was set up to an injection speed 20 cm^3/s, 40 tons of clamping force, and velocity/pressure (V/P) switchover at 95% volume filled. Cooling time was set to 15 seconds. The first testing was conducted to validate the simulation results obtained from Moldflow in CHAPTER 5. The second experimental results validate the impact the melt modulation technique has on final product quality. The recommended processing conditions for all three resins used for the experiments are summarized in Table 6-1.

7.3.1 Packing Processing Parameters Experimental Results

The Taguchi method used for the experiment with L9 (3^3) orthogonal array and included three parameters only: mold temperature, packing pressure, and packing time. The melt temperature was not included in the experiment processing parameters for two reasons: First, it takes time to heat up and cool down polymer melt in cold-runner injection molding machines, so it is not possible to change the melt temperature rapidly. Second, having the molten polymer sit in a barrel for an extended period of time until the melt temperature reaches the requested value is undesirable as it may overheat the polymer and cause melt degradation.

The ASTM D638 – Type I dog-bone specimens were molded according to the processing parameters listed in Table 7-1. For each processing condition, samples were selected after the machine was running for at least ten cycles. These parameters are consistent with the parameters used in the Moldflow simulations. The only change was that the cooling time was reduced to 15 seconds, which is sufficient for the molten polymer to completely solidify. The levels of each parameter selected for the experiment and the modified L9 array are shown in Table 7-2.

Table 7-1: Experimental Processing Parameters

Material	Parameter	Symbol	Level 1	Level 2	Level 3
PMMA	Mold Temperature (°C)	A	38	58	80
	Packing Pressure (MPa)	B	30	75	120
	Packing Time (s)	C	2	8	15
PC	Mold Temperature (°C)	A	80	91	102
	Packing Pressure (MPa)	B	30	75	120
	Packing Time (s)	C	2	8	15
GPPS	Mold Temperature (°C)	A	30	45	60
	Packing Pressure (MPa)	B	30	75	120
	Packing Time (s)	C	2	8	15

Table 7-2: Modified L9 (3^3) Orthogonal Array

Experiment	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	2	3
5	2	3	1
6	2	1	2
7	3	3	2
8	3	1	3
9	3	2	1

7.3.1.1 Birefringence

Birefringence of the ASTM D638 – Type I dog-bone specimens was analyzed using a polarimeter (PF-100SF). The specimens were observed through a green 570 nm band-pass filter for better clarity. The birefringence results from Taguchi L9 method of nine experiments for all three translucent materials are presented in Figure 7-1, Figure 7-2, and Figure 7-3. The birefringence is not visible for Polymethyl Methacrylate (PMMA).

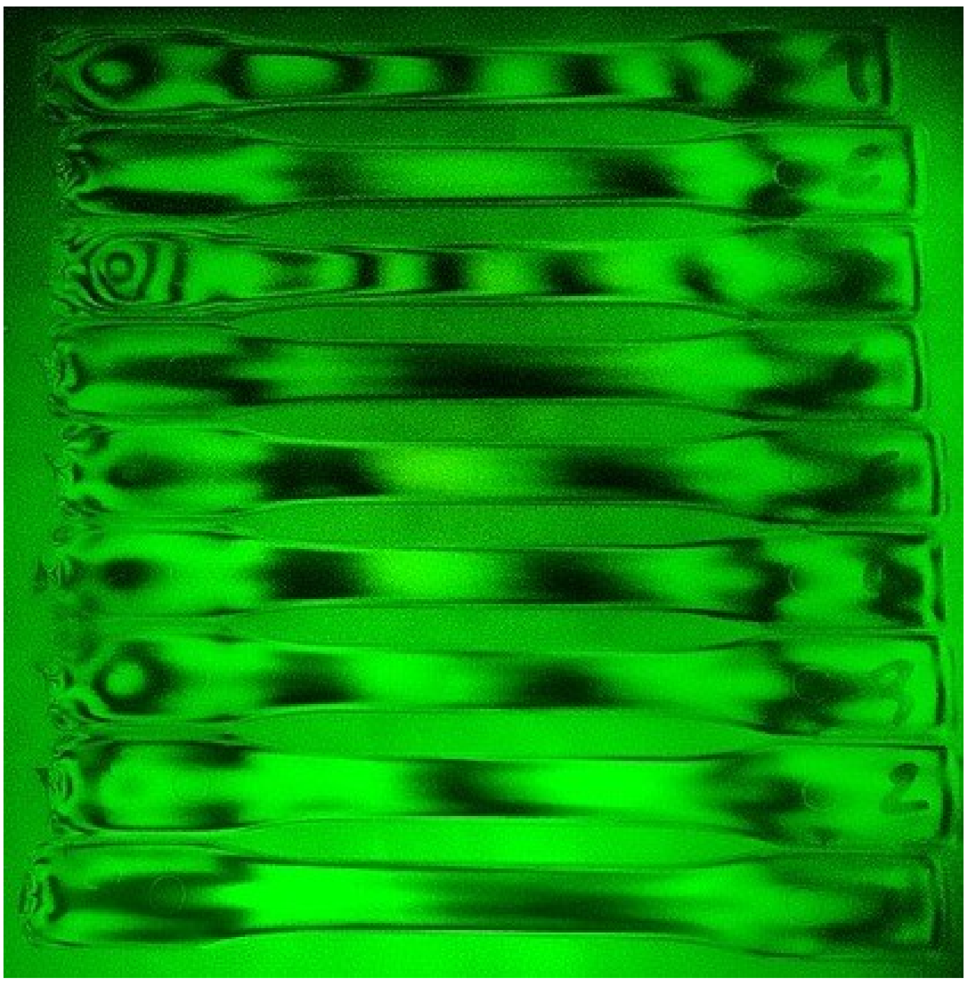


Figure 7-1: GPPS Birefringence Result from Taguchi L9 Method (ASTM D638 – Type I)

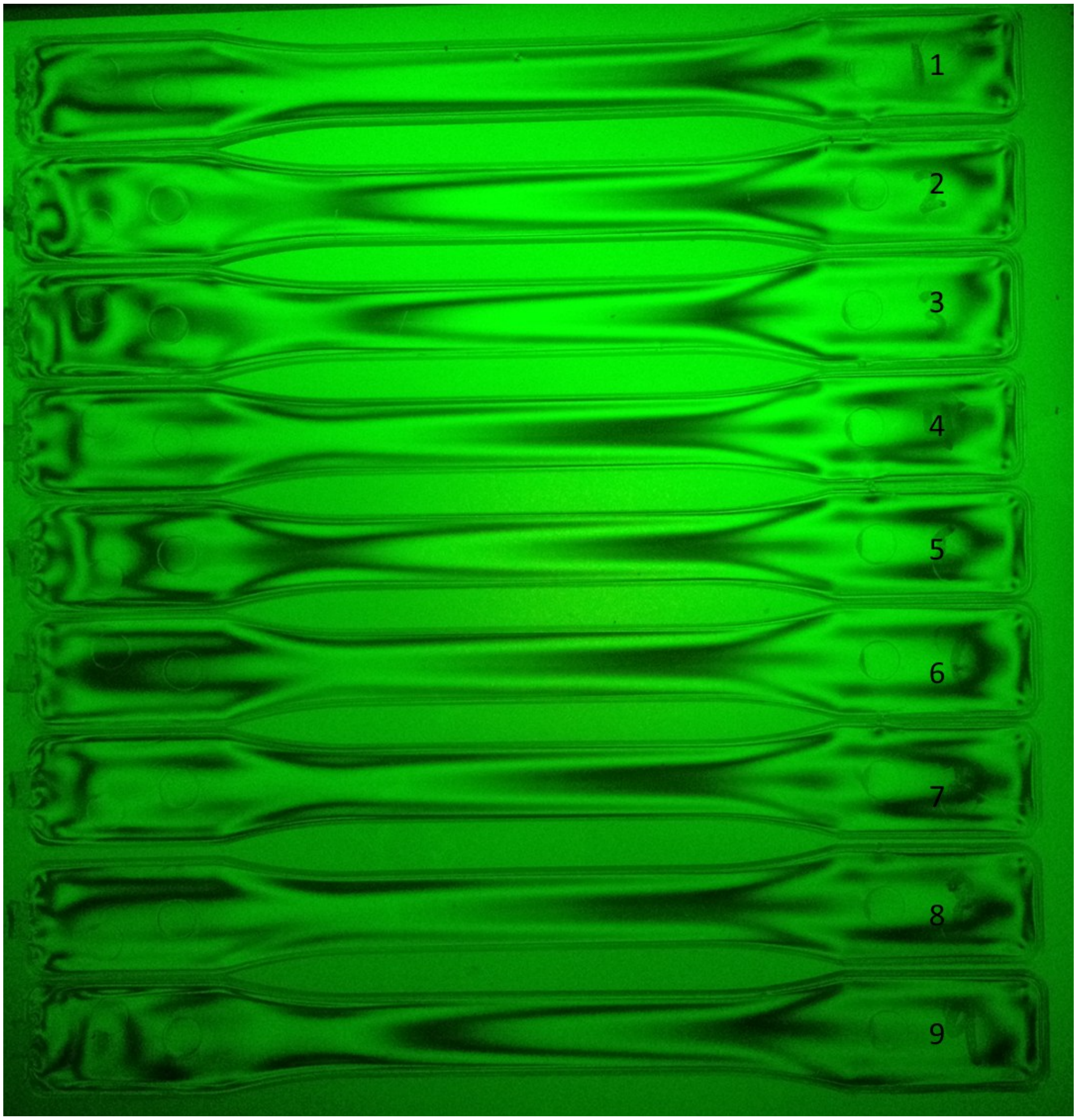


Figure 7-2: PC Birefringence Result from Taguchi L9 Method (ASTM D638 – Type I)

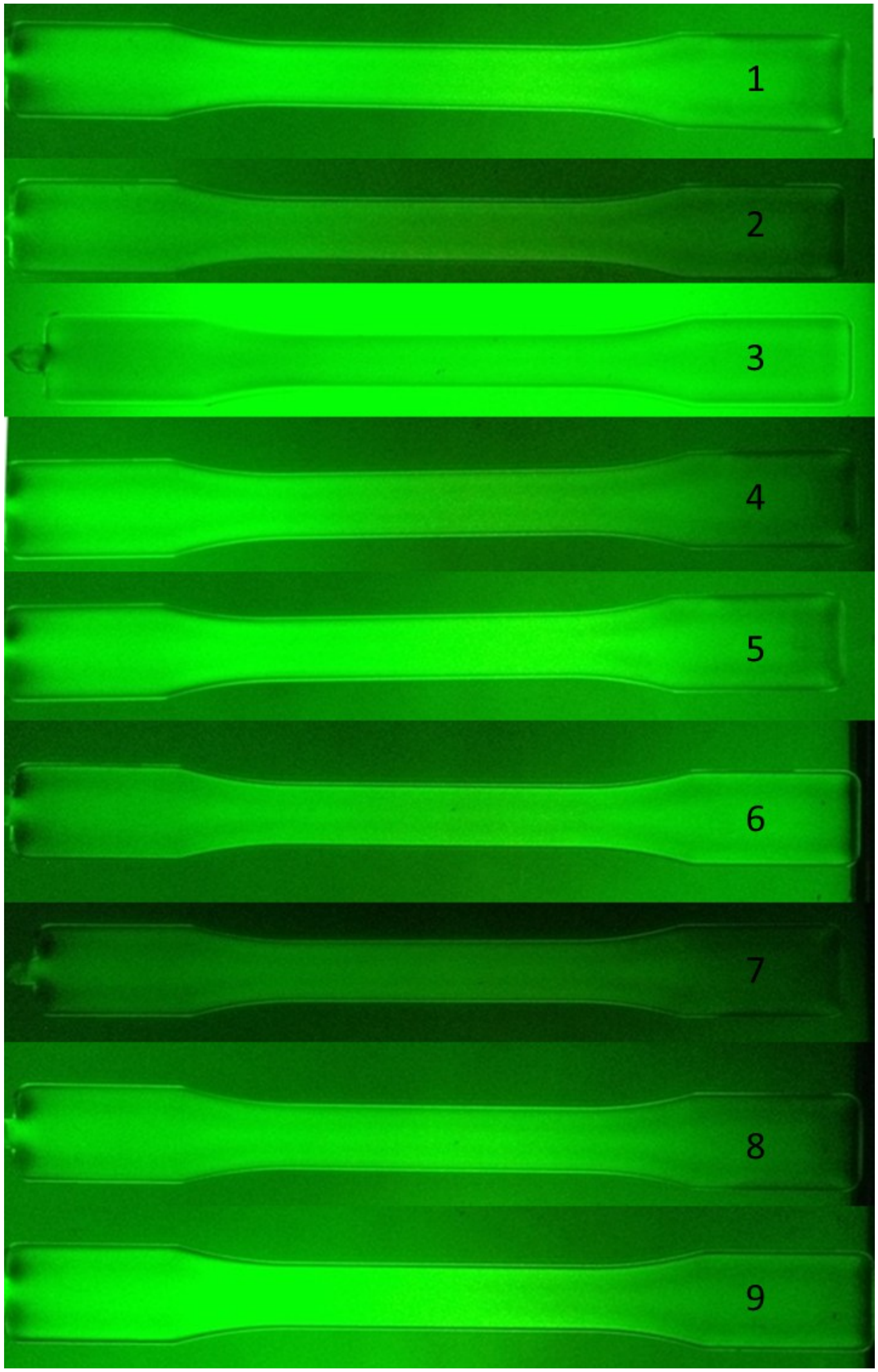


Figure 7-3: PMMA Birefringence Result from Taguchi L9 Method (ASTM D638 – Type I)

The samples from each experiment were collected and used to calculate retardation from equation (3-8). The retardation plots from nine experiments for GPPS and PC are shown in Figure 7-4 and Figure 7-5. The linear distance measured from the gate position is represented by the horizontal axis.

Retardation results show significant variation between each experiment. To show the effect of the packing parameters on retardation, the maximum value of retardation of GPPS and PC from each experiment was collected to generate Taguchi plot as shown in Figure 7-6 and Figure 7-7.

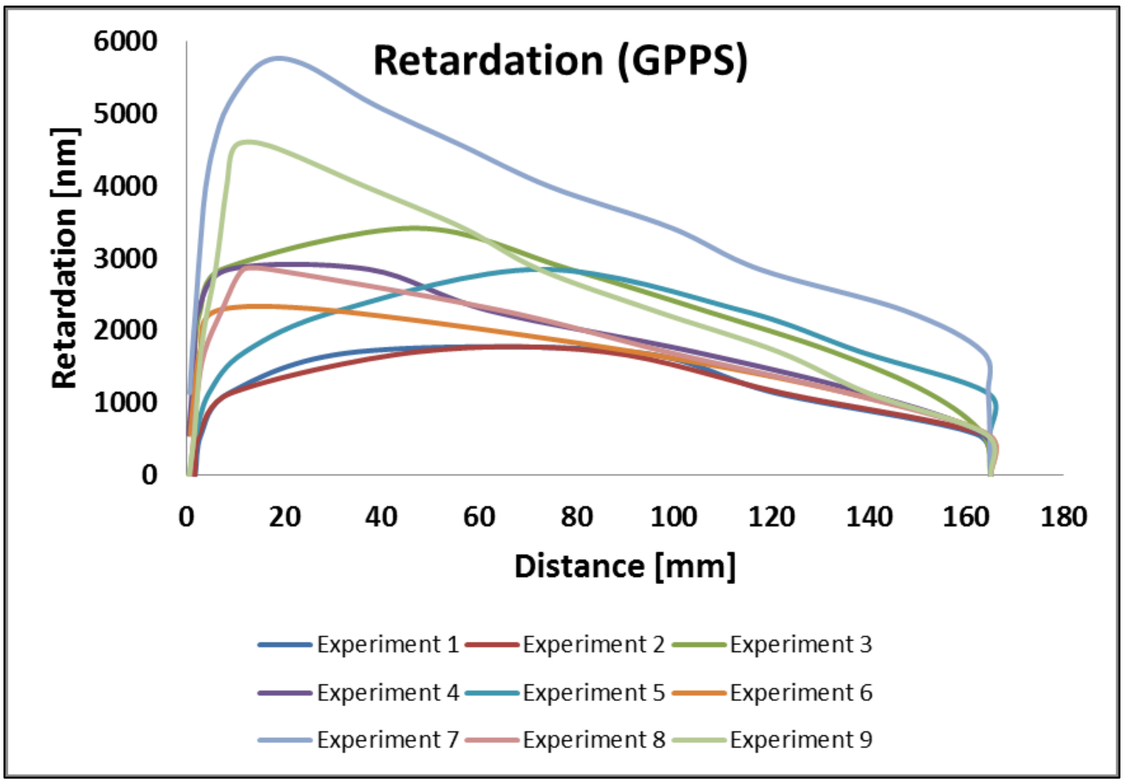


Figure 7-4: Retardation Plot - GPPS (ASTM D638 – Type I)

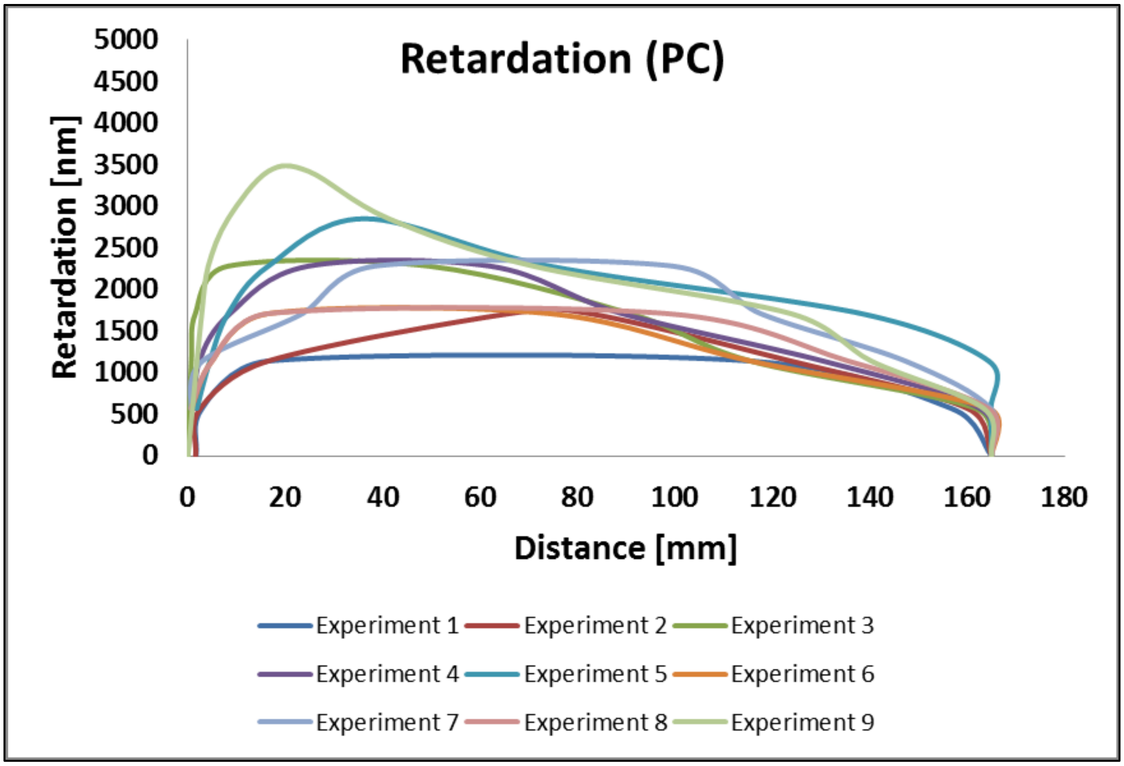


Figure 7-5: Retardation Plot – PC (ASTM D638 – Type I)

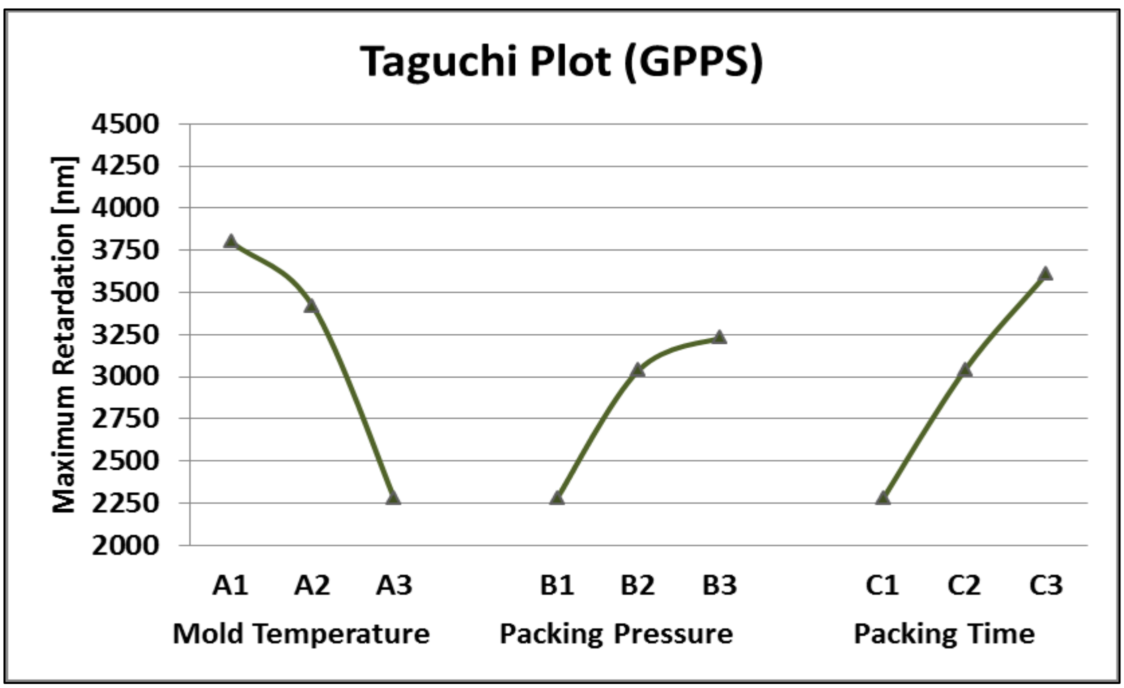


Figure 7-6: Taguchi Plot of Maximum Retardation - GPPS (ASTM D638 – Type I)

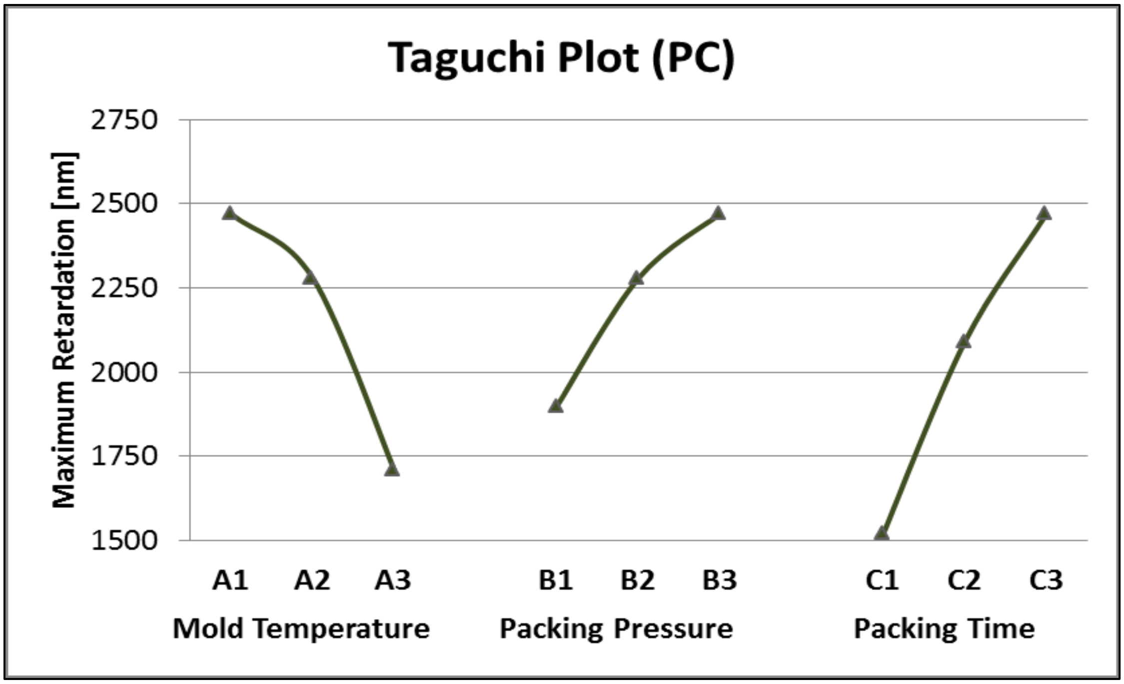


Figure 7-7: Taguchi Plot of Maximum Retardation – PC (ASTM D638 – Type I)

7.3.1.2 Tensile Test

From each material and experiment, five ASTM D638 – Type I dog-bone specimens were tested to different processing conditions using MTI Phoenix tensile test machine with a load cell capacity of 10,000 lbs. to investigate their strength. The results for the average maximum tensile load of GPPS, PC and PMMA are shown in Figure 7-8, Figure 7-9, and Figure 7-10 respectively. The results of the average maximum tensile stress of GPPS, PC and PMMA are illustrated in Figure 7-11, Figure 7-12, and Figure 7-13 respectively.

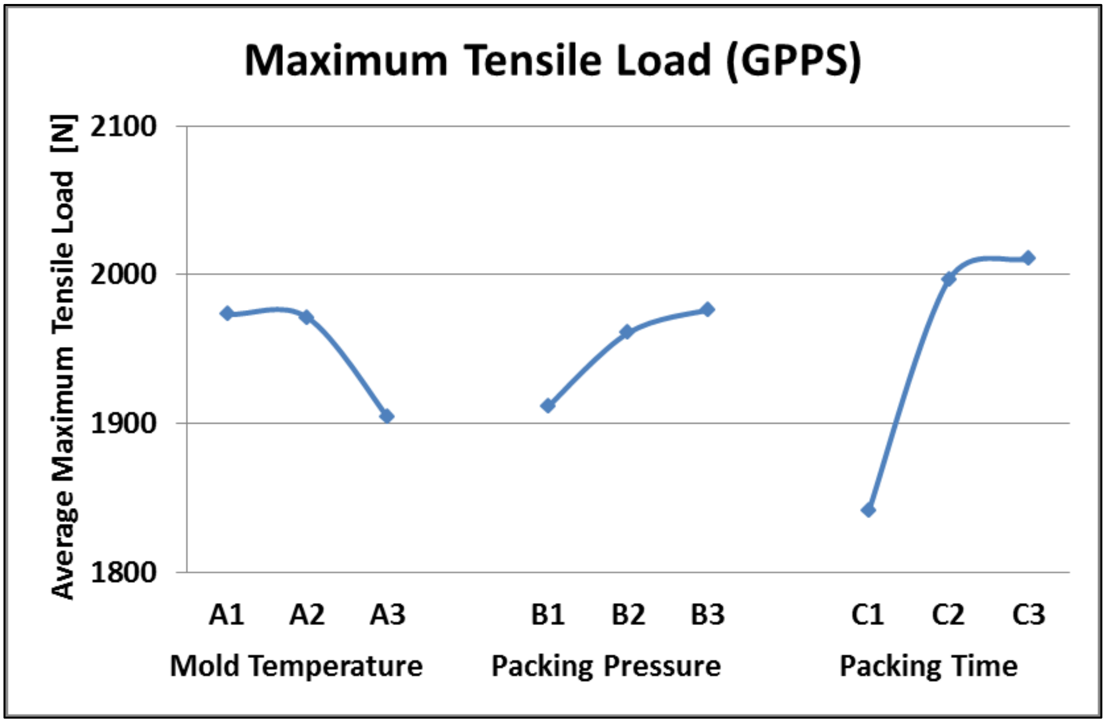


Figure 7-8: GPPS - Average Maximum Tensile Load (ASTM D638 – Type I)

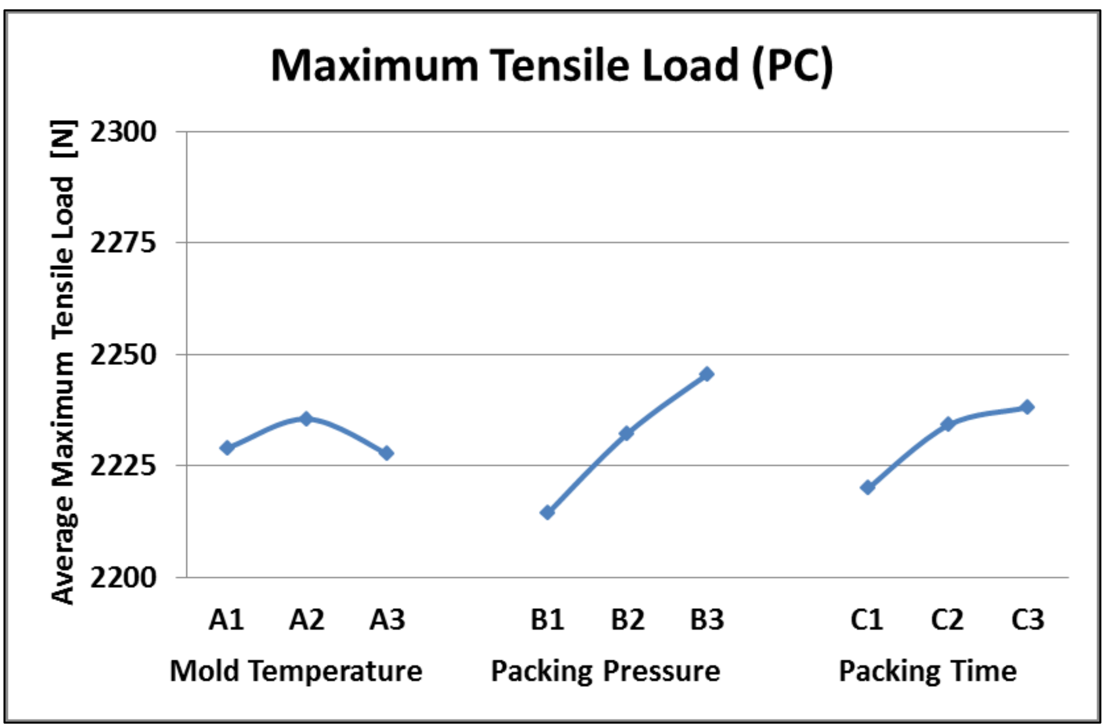


Figure 7-9: PC - Average Maximum Tensile Load (ASTM D638 – Type I)

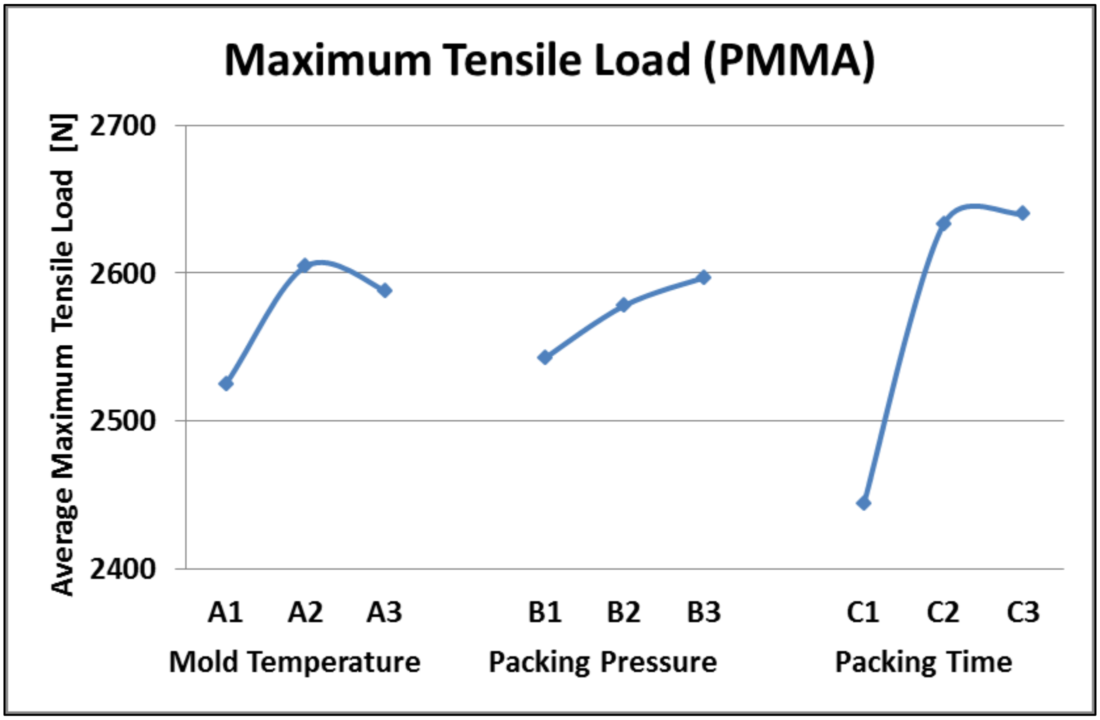


Figure 7-10: PMMA - Average Maximum Tensile Load (ASTM D638 – Type I)

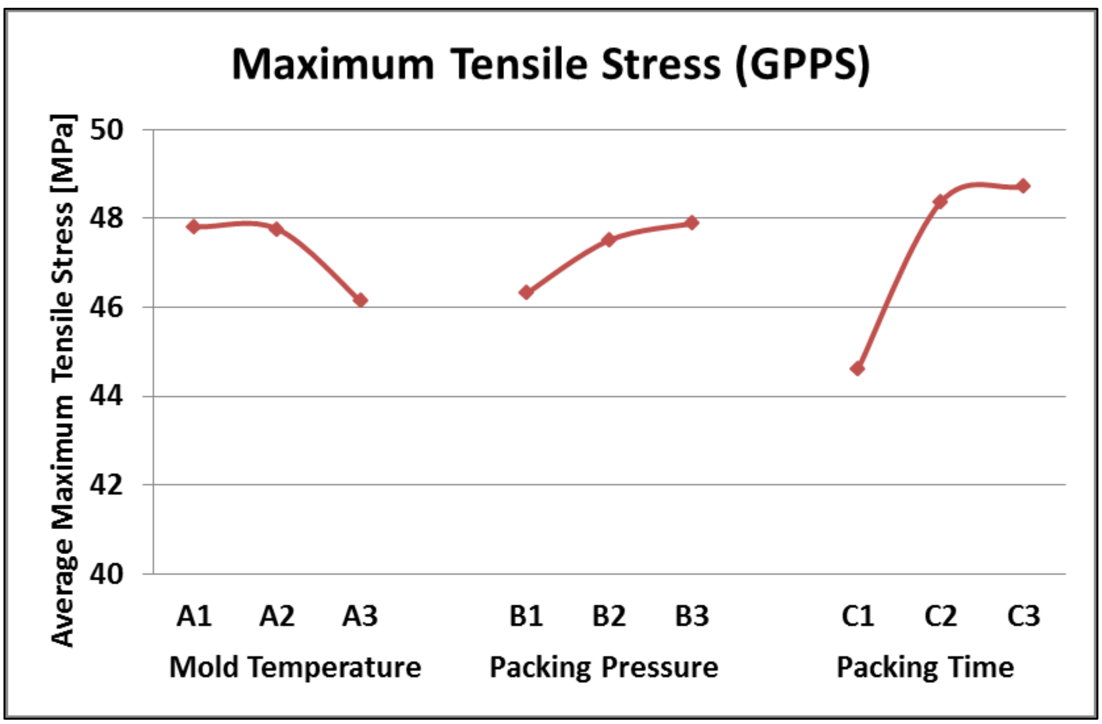


Figure 7-11: GPPS - Average Max Tensile Stress (ASTM D638 – Type I)

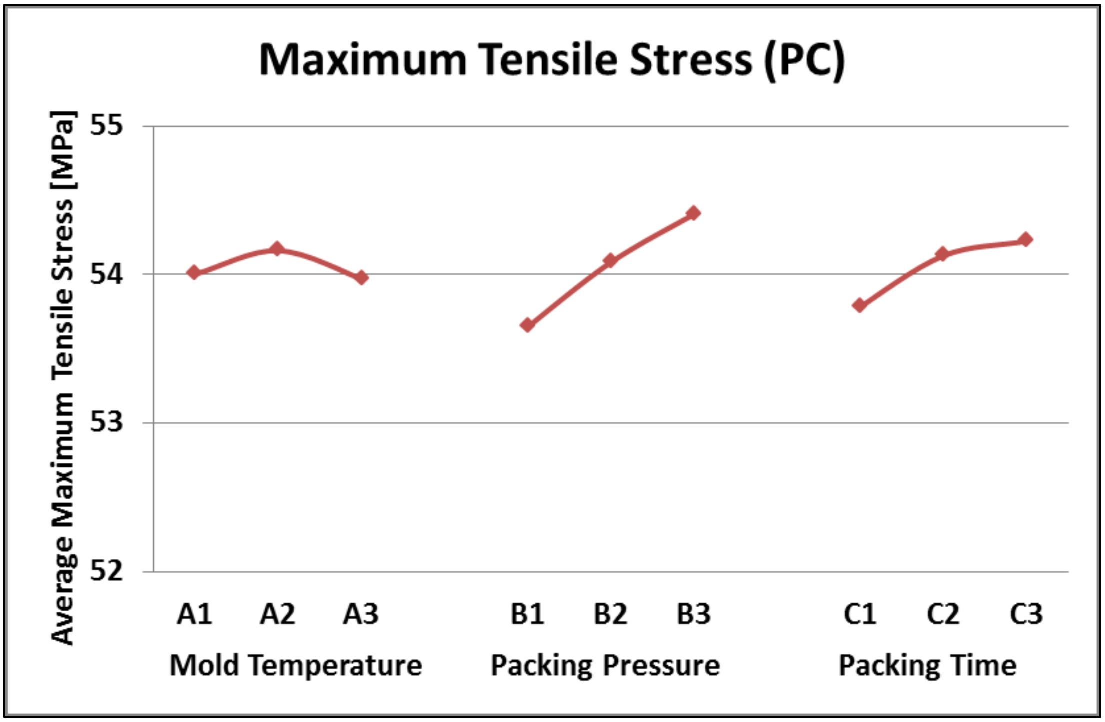


Figure 7-12: PC - Average Max Tensile Stress (ASTM D638 – Type I)

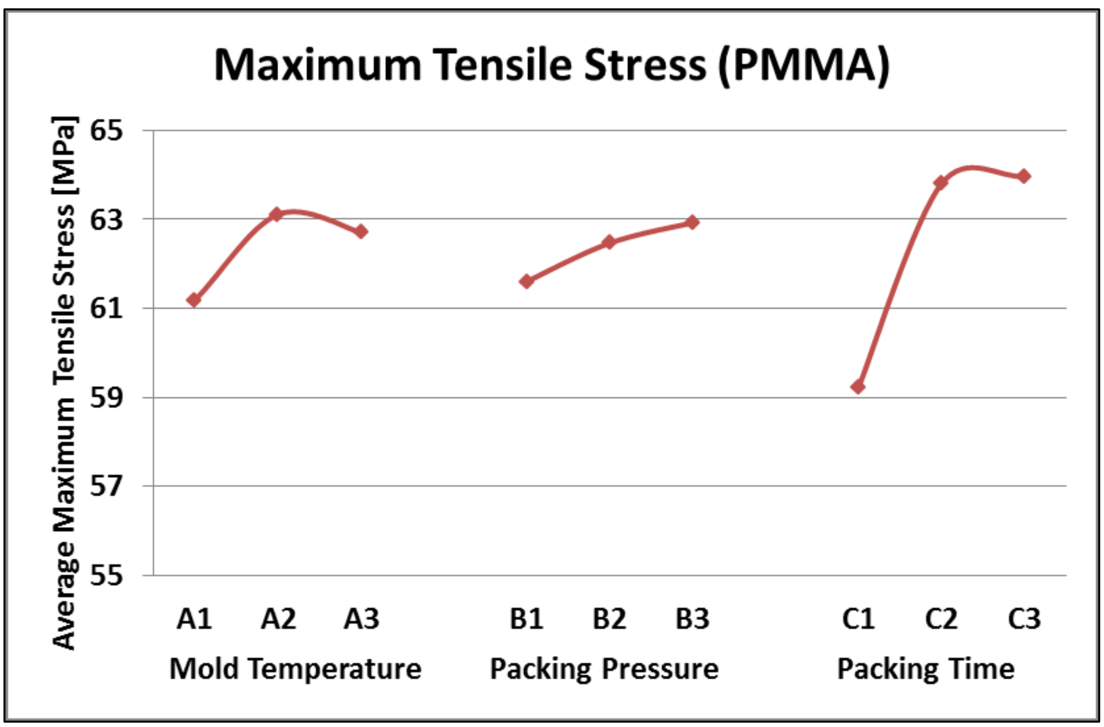


Figure 7-13: PMMA - Average Max Tensile Stress (ASTM D638 – Type I)

7.3.2 Melt Modulation Experimental Results

The following experiments have been conducted to demonstrate the ability of the modular melt modulation to control the packing parameters; and hence, impact the final product quality. This has been accomplished by manipulating the packing parameters during an injection molding cycle using the modular melt modulation system. The modular melt modulation system experiments included testing of three different packing control routines; packing pressure, packing time, and valve angle control. Since the three transparent materials have had similar performance in previous testing, only STYRON® 685D (GPPS) was selected for these experiments [58]. The Nissei injection molding machine model number PS40E5ASE with the specifications in Table 5-2 was used for the experiments with the recommended processing conditions from Table 6-1 and level 2 from Table 7-1 unless otherwise noted. The mold insert used for the following three experiments has a two cavity configuration and is shown in Figure 7-14

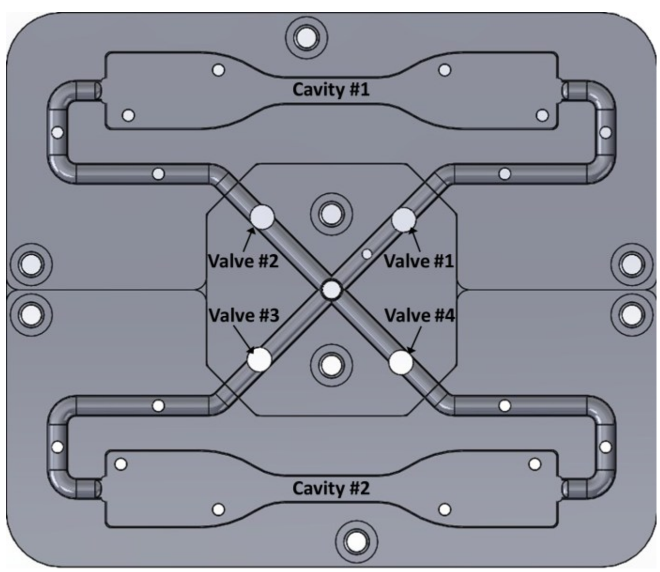


Figure 7-14: ASTM D638 – Type IV Mold Insert Used for Experiments

The packing profile of the injection molding machine has a two-level step function, each with full range from 0%-100% of maximum packing pressure the machine. Prior to conducting each experiment, the two cavities were initially filled to about 95% of their total volume at zero packing pressure. This was achieved by shutting off valves 2 and 3; while keeping valves 1 and 4 fully open. After that, packing pressures for level 1 and level 2 were increased equally until the two cavities were completely filled. This established the lower limit for the packing pressure required for the experiments. To establish the upper limit of the packing pressure required, both levels 1 and 2 were increased equally until the cavities began to flash (excess polymer). After defining the packing pressure range for the experiments valve 1 remained open and valve 4 was being controlled throughout the following experiments.

7.3.2.1 Packing Pressure Control

To manufacture parts with different packing pressure profiles, the operating control valves must have different angular positions. In this experiment, the packing pressure has been restricted by turning only one valve at a constant packing time. Since only two cavities were tested, valves 2 and 3 were closed throughout the entire injection molding cycle. Valve 1 remained open during the entire injection molding cycle, while valve 4 was closed during the packing phase only. The birefringence and tensile test results have been obtained for each cavity. Figure 7-15 illustrates the birefringence of each cavity.

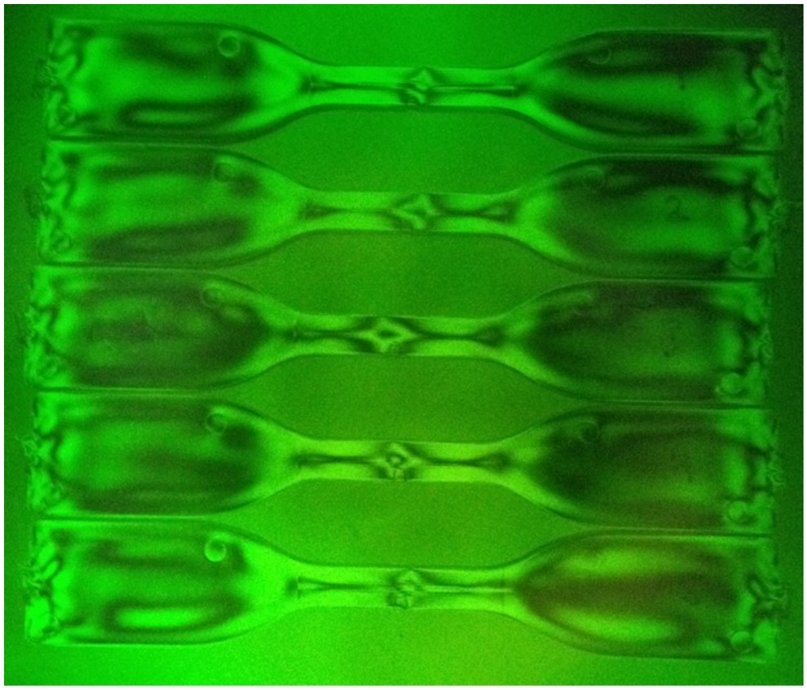
7.3.2.2 Packing Time Control

Similar to the process of controlling packing pressure, packing time control is applied at the end of the filling cycle at constant packing pressure for a specific time. In this experiment, the processing parameters of level 2 from Table 7-1 have been used. The packing time control was applied on valve 4 after 2 seconds from the time the injection cycle began. During a series of 10 parts made, the average injection molding time was 1.36 seconds. The experiment started with valve 1 fully open throughout the cycle and valve 4 was shutting off for 8 seconds. Valves 2 and 3 were remained closed. The birefringence results of each cavity are shown in Figure 7-16.

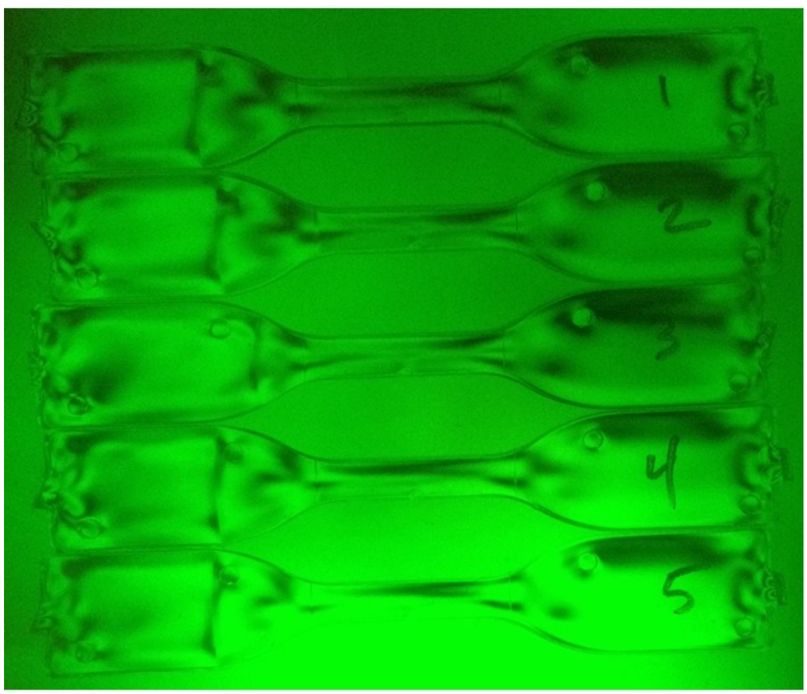
7.3.2.3 Valve Angle Control

Another useful method to measure the effect of melt modulation technique on packing parameters is to vary the angle of one of the valves at constant packing pressure and time. However, rather than shutting off valve 4 completely as in the previous tests, the valve angle was set to 45^{o} during the packing phase. Valves 2 and 3 were closed, while valve 1 remained open during the entire injection molding cycle. The birefringence results of the valve angle control of each cavity can be seen in Figure 7-17.

The results for average maximum tensile load and stress for both cavities with respect to all the three control methods were also recorded and shown in Figure 7-18 and Figure 7-19 respectively.

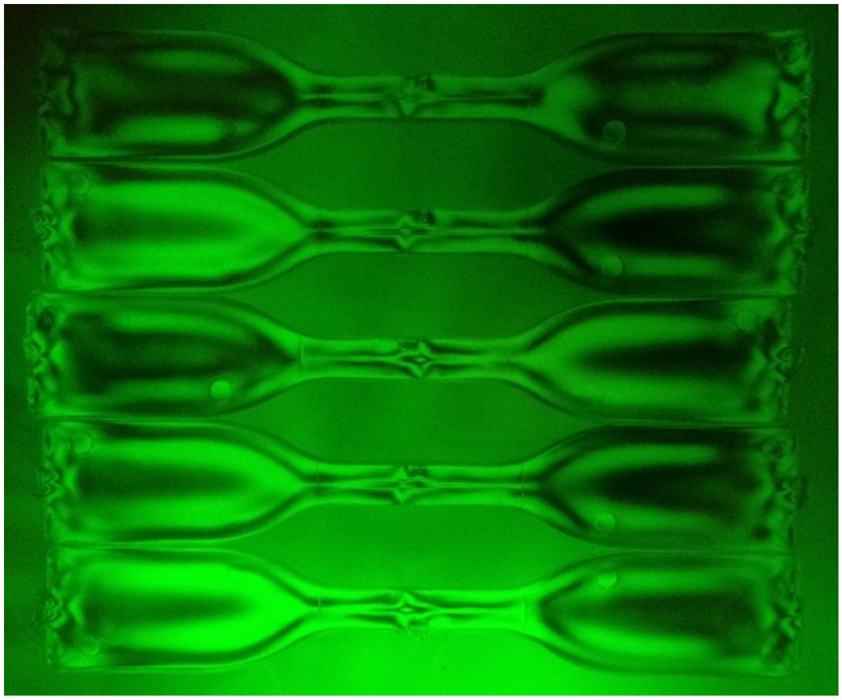


Cavity #1

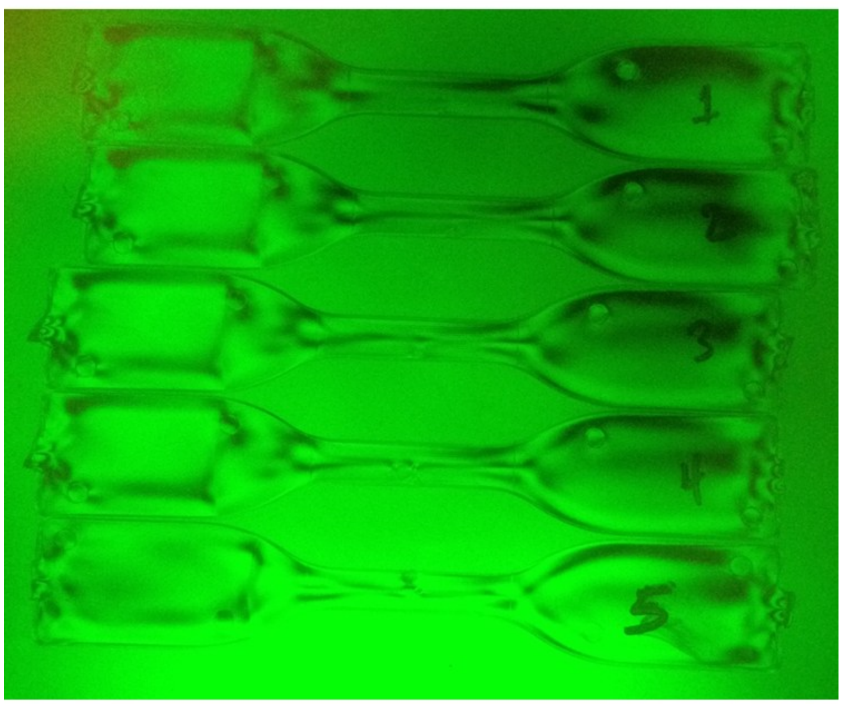


Cavity #2

Figure 7-15: Birefringence - Cavity #1 vs. Cavity #2 (Packing Pressure Control)

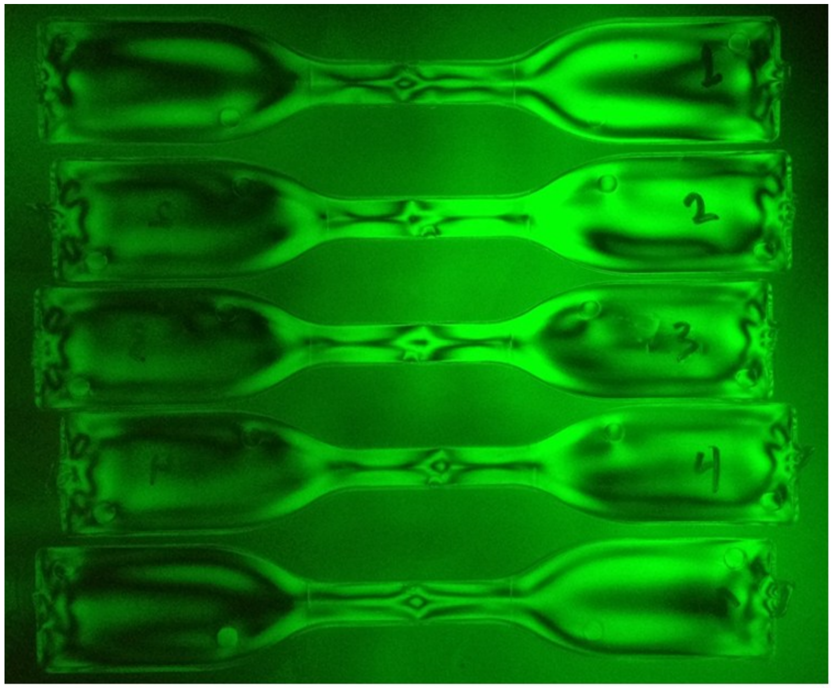


Cavity #1

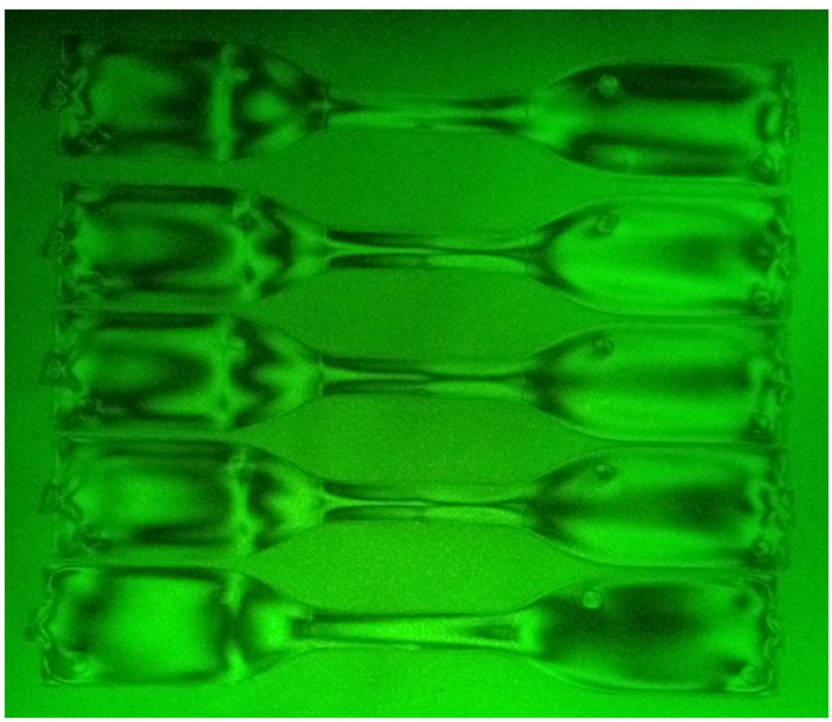


Cavity #2

Figure 7-16: Birefringence - Cavity #1 vs. Cavity #2 (Packing Time Control)



Cavity #1



Cavity #2

Figure 7-17: Birefringence - Cavity #1 vs. Cavity #2 (Valve Angle Control)

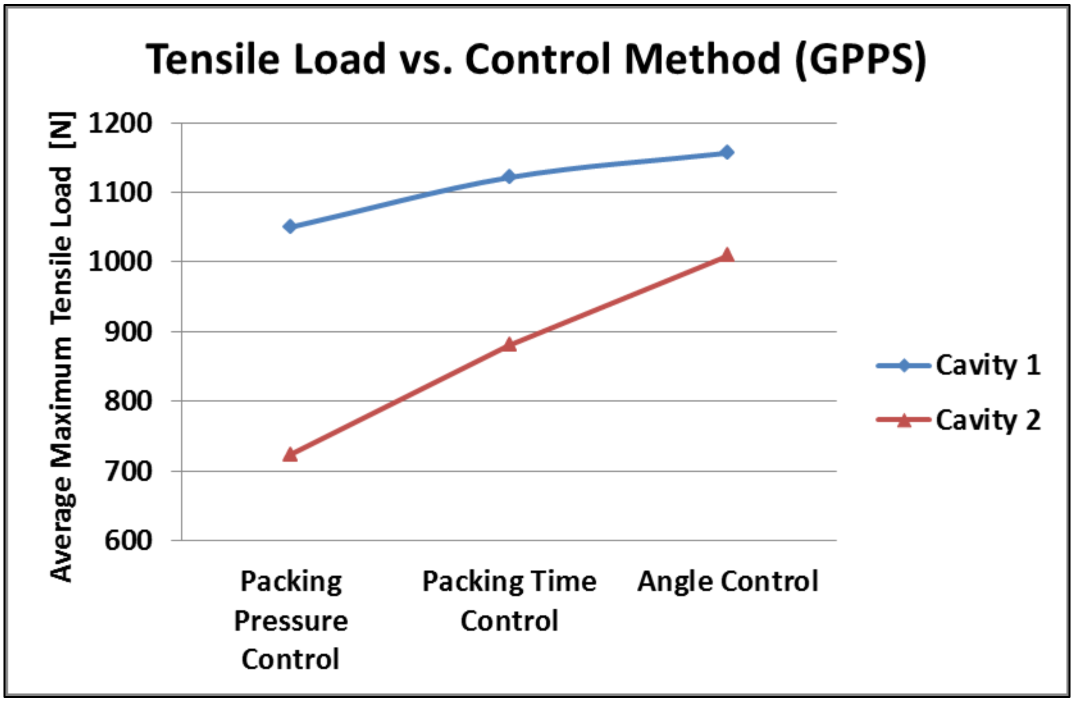


Figure 7-18: Average Maximum Tensile Load - Cavity #1 vs. Cavity #2 (All Control Methods)

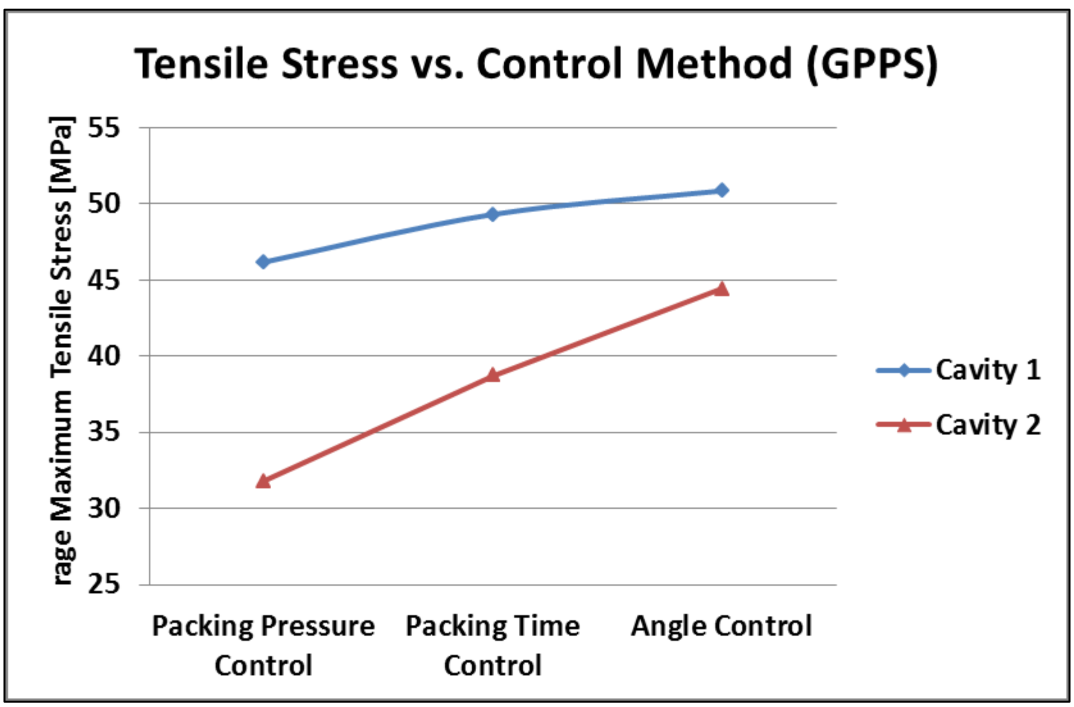


Figure 7-19: Average Max Tensile Stress - Cavity #1 vs. Cavity #2 (All Control Methods)

7.4 Discussion

The experimental results clearly show that processing parameters significantly affect the properties of injection molding products. Mold temperature, packing pressure and packing time can impact the final quality of the molded product. Increasing packing processing parameters tends to increase the molecular orientation, which is evidenced through higher birefringence and optical retardation. It also increased part tensile strength. Of the three clear polymers, STYRON® 685D (GPPS) had higher birefringence and more variations in optical retardation than Polycarbonate LEXAN™ (PC). Polymethyl Methacrylate Plexiglas® V-920 (PMMA) showed no visible birefringence.

In the second set of experiments, the results showed that turning the control valve to restrict packing pressure can have a direct influence on the properties of cold runner injection molding parts. Two cavities were tested under the same conditions with one exception, valve angle. The first cavity (cavity 1) had full melt flow and packing since the valve was open during the whole injection molding cycle. The second cavity (cavity 2) had full melt flow but with restricted packing parameters, where the valve was either completely closed or restricted to 45^{o} angle for a specific duration of packing time. The results showed that the first cavity consistently exhibited higher birefringence than the second cavity. The birefringence of the second cavity increased under angle control because there was packing pressure passing through the valve.

In terms of physical properties, the second cavity demonstrated lower tensile strength and tensile stress than the first cavity. This is due to the pressure drop across the valve caused by either closing the control valve or restricting it. When comparing all three control methods, angle control generated parts with higher tensile strength and stress than the other two control methods. That is because packing pressure passed through the valve. Packing time control showed slightly higher tensile strength than packing pressure control. This is due to the fact that the valve was kept shut for a shorter period of packing time than the packing pressure control.

The new melt modulation system has been validated analytically and experimentally in the lab. However, it still has to be endorsed in the market place. The next chapter discusses the market research and the product feasibility for commercialization as well as presenting several financial case studies for the modular melt modulation system.

CHAPTER 8 – MARKET ANALYSIS

The melt modulation technology has been proven to work well in the lab. It has provided possibilities that were not previously available for cold runner injection molding machines. However, it still has to be validated in the market place. There are many early- and mid-stage academic discoveries that have worked well in lab, but never successfully made it to the market place. In order for a technology to make it in a market place, it has to meet a specific need or fulfill a poorly addressed application. Success with such innovation requires a good understanding of the technical and business fundamentals that govern their application. Even then, the risk of falling under the term “Technical success and Commercial Failure” is still high. According to Greg Stevens, president of WinOvations, a new product research and consulting firm in Midland, Michigan, only 2 products are launched out of every 3,000 ideas, and only one of those succeeds [6]. The challenge always is how to reduce the risk of failure and make sure that technological innovations such as the modular melt modulation system becomes a successful “market ready” technology.

8.1 Market Size

Almost every product we touch throughout the day has been produced by a manufacturing process. The majority of those products are made by plastics. According to a recent US Census, there are 333,220 plastics and rubber industry machinery manufacturing in in the US [61].

The global demand for plastics resin production has been growing at a steady pace. According to Figure 8-1, the global plastics resin production from 1950 to 2010 has a solid up trend up until 2007. In 2008, the global demand for plastics resin fell slightly for the first time in 34 years, caused by the global financial crises.

Figure 8-1: Global Plastics Resin Production from 1950-2010 [26]

The total worldwide market for injection molding machines is estimated at an annual growth rate of 15.5% between 2009 and 2013. The molders' demand in Eastern Europe, China and Latin America, is the driving force behind this positive trend with growth rates of 23.1%, 19.4% and 21.5% respectively [23].

According to a recent market report published by Transparency Market Research, the global market for injection molded plastics was estimated to be worth USD 168 billion in 2010 which is expected to reach a market worth of USD 252 billion by 2018, growing at a Compound Annual Growth Rate (CAGR) of 5.3% from 2013 to 2018. In terms of material consumption, 79,079.5 kilo tons were consumed in 2010 which is expected to reach 116,171.4 kilo tons by the end of 2018, growing at a CAGR of 4.9% from 2013 to 2018. In 2011, North America and Europe share about one third of the market, which was the second largest market after Asia Pacific being the largest market for injection molded plastics, sharing 37.2% of the market. The growth of the global house ware and personal care market, where polypropylene, one of the major resins used for injection molded plastics, is majorly used, is one of the main factors driving the global injection molded plastics market. Another growth area that is contributing to the global sales for injection molded plastics is the global packaging market, mainly rigid packaging. With 31.9% of the market in 2011, the packaging industry captured the biggest market share, followed by the consumables and electronics, sharing 30.1% of the market. The fastest growing market in the injection molding industry is the electronics segment, growing at a CAGR of 5.1% from 2013 to 2018 [24].

Another growth segment is the injection molding machine market, which displayed strong momentum in 2011. Compared with the Chinese market, Germany and the U.S. increased over 10% in output value and Japan 8.7%. Given the strong demand by the international market, China's injection molding machine exports in 2011 increased by a large margin, with annual cumulative export value of US$824 million, a year over year (YoY) rise of 32.0%. The Chinese injection molding machine industry in 2011 grew with annual sales of USD $3.967 billion. With an output of 27,000 units produced in

2011, Haitian International is the largest injection molding machine enterprise in China and even the world. Other Chinese companies that have shown strong competition producing over 10,000 units per year include The Chen Hsong Group, Borch Machinery, Guangdong Kaiming Engineering Co., Ltd. and Tederic Machinery Manufacture (China) Co., Ltd. Other producers such as Demag, Engel, Husky, NISSEI, TOYO and Toshiba have also successively increased their strength in the injection molding machine market [25].

In the first quarter of 2011, Plastics News conducted a survey showing that 30% of the old makers in the United States have shown an increase in profit level [26]. At the same time 17% of the mold makers have seen decrease in profit levels and the remaining reported no change. Figure 8-2 shows the profit and the employment levels for the US mold makers that were surveyed during the first quarter of 2011.

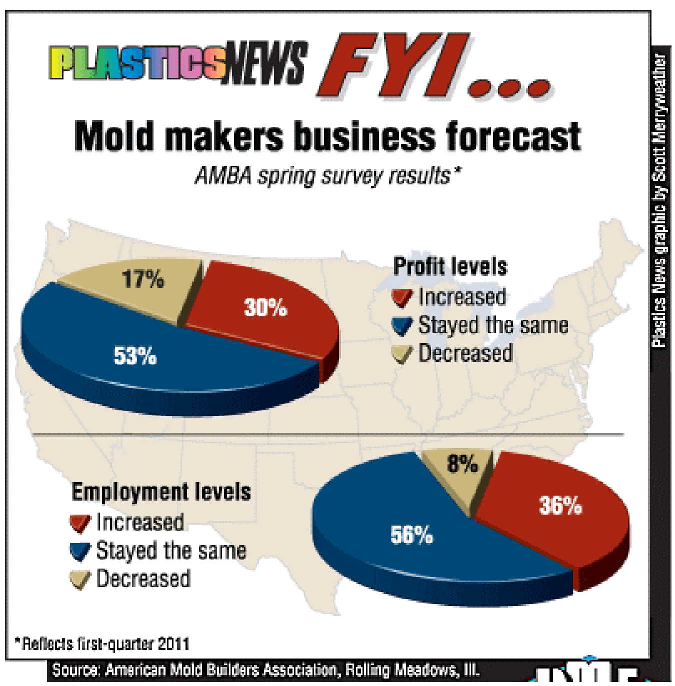


Figure 8-2: US Mold Makers Profit and Employment Levels [26]

8.2 Potential Opportunity for Modular Melt Modulation System

The injection molding market is big and growing. Although hot runner molding has been gaining popularity in recent years, it has only captured an estimated 30% market share [3]. Cold runner systems still dominate with the majority market share in the industry because of its low investment cost and simplicity (easier to operated, manage, and maintain). Also, hot runner molds are only feasible in certain injection molding applications. Hot runner systems are ideal for high volume and long production cycles, highly complex design with automated production, molding expensive polymer, family molding and for products that require blemish-free surface. However, there are many applications where cold runner can be more economically feasible. The following case studies demonstrate when hot runner molding makes financial sense.

8.2.1 Financial Feasibility - Hot Runner Versus Cold Runner Systems

Hot runner systems can reduce injection cycle time, which yields higher productivity. Also, since it does not have runners, there is no wasted runner material. This contribute to the reduction of piece part cost. In addition, the absence of the cold runner saves added labor time required for runner handling, gate trimming, and regrinding. These factors contribute to the majority of the savings. Often, the selection process between cold runner and hot runner systems is dictated by financial factors, but these factors are not sufficient to conclude that hot runner is always the best choice. To examine the financial feasibility of replacing cold runner with hot runner system, five case studies have selected. The case studies are presented here to demonstrate the circumstances where hot runner systems may provide better economic value and cost savings. The focus of these studies was strictly financial. All five cases, case study 1 through case study 5 are illustrated in Figure 8-3, Figure 8-4, Figure 8-5, Figure 8-6, and Figure 8-7 respectively. The results are based on calculations that were derived from a model introduced by one of the hot runner manufactures [19], which utilized it as a tool to demonstrate the first year savings generated by incorporating hot manifold systems. The case studies were investigated using the following assumptions:

1. Parts can be manufactured by either hot runner or cold runner machines with acceptable product quality.
2. Four cavities output with a 4H cavity runner configuration
3. Runner size:
    a) Sprue: 2.375” long with an average diameter of 1/4”
    b) Runner: 6” long with a 3/16” diameter
    c) Sub-runner: 2” long with a 1/8” diameter
4. Material: Thermoplastic resin with a mass density of 0.04329 lb/in^3
5. A cycle time of 18 seconds, which includes filling, packing and cooling time
6. Eight hours work day with one shift/day, and five working days per week.
7. Cold runner regrind of 10%.
8. Cycle time saving contributed to hot runner mold: 15%
9. Machine operating costs: $16/hour
10. Operator rate: $20/hour
11. Manifold cost: $15,000 (including four hot manifolds and supporting equipment)
12. Shop hourly rate of $60/hour

13. Set-up time of one hour with an additional hour/week for maintenance

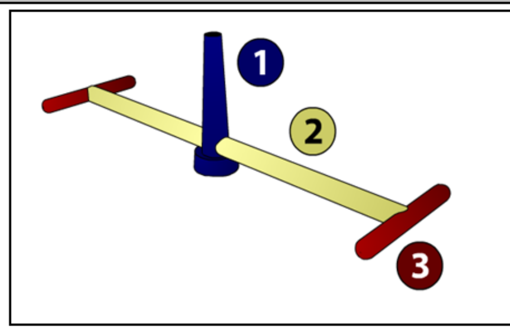
14. Electricity cost of $0.35 per kW

As illustrated in Figure 8-3, for a low cost polymer (i.e. $3/lb.) and low production volume, there is clearly no savings at all. The total money gained was $2,411.65, which does not cover the cost of the hot manifold. In this case, investing in a hot runner system would result in a loss of $12,737.55. Also, if the volume continues to be around the same rate, the molder will have to wait about seven years to break even. Therefore, staying with a cold runner mold for this case is a better choice.

Case No. 1: (1) Low cost polymer ($3/lb.), (2) Low production volume (16,000 parts)

INPUT

1. Select Cold Runner Layout
_4H_Cavity
Enter Material Cost/pound
$3.00



2. Input Dimensions

Section	Diameter	Length	Qty
1	0.2500	2.3750	1
2	0.1875	6.0000	1
3	0.1250	2.0000	2

Density	Area	Volume	Weight (lbs)
0.0433	0.0491	0.1166	0.0050
0.0433	0.0276	0.1657	0.0072
0.0433	0.0245	0.0491	0.0021

Total Weight (lbs) = 0.0143

3. Number of Mold Operating Time	
Cold Runner Cycle (seconds)	18
Hours Per Shift (hours)	8
Shifts Per Day	1
Days Per Week	5
Weeks Per Year	2
Percentage Regrind (10% max)	10%

4. Enter Cycle and Labor Costs	
Cycle Time Savings (10-35%)	15%
Machine Cost Per Hour	$16
Employee Cost Per Hour	$20

5. Initial and Ongoing Costs	
Estimated Hot Runner System Cost	$15,000
Shop Rate Per Hour	$60
Additional Setup Time (hours)	1
Periodic Maintenance Cycle (weeks)	1
Maitenance Time (hours)	1
HRS Power (dollar per kilowatt hour)	($0.35)

OUTPUT

Output Summary		
Weight of Runners (lbs)		0.0143
Total Cost of Runner	$	0.04
Total Time Mold is Run (sec/year)		288,000
Number of Cold Runners Molded		16,000
Total Cost of Runners Per Year	$	688.50
Total Cost After Regrind	$	619.65
Cycle Time reduction Savings	$	192.00
Total Hours Machine is Run		80
Total Machine Time Cost	$	1,280.00
Total Employee Time Cost	$	1,600.00
Electrical Power Cost	$	(30.80)
Additional Labor	$	180.00
Gross Savings	$	2,411.65
Gross Expenses	$	15,149.20

Total Savings - First Year!!!	
$	(12,737.55)

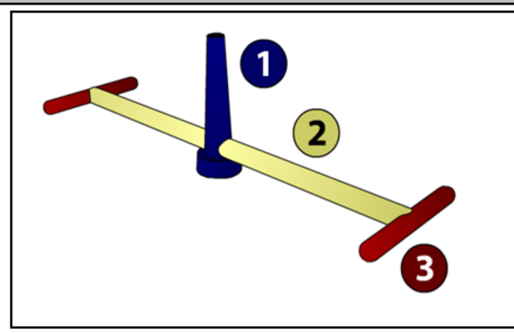
Figure 8-3: Case No. 1 – Financial Feasibility of Hot Runner Mold (4-H Cavity Design)

In the second case study, shown in Figure 8-4, all parameters remained the same including the cost of the polymer; except that the annual production volume was increased significantly. Based on these assumptions, the runner costs $0.04 each. When the production rate increased from 16,000 units to 104,000 parts, there was a saving of $35.91 generated from the volume increase in the first year. This suggests that a hot runner system might be more economically feasible as long as the production volume required exceeds the minimum production rate threshold of 104,000.

Case No. 2: (1) Low cost polymer ($3/lb.), (2) High production volume (104,000 parts)

INPUT

1. Select Cold Runner Layout
_4H_Cavity
Enter Material Cost/pound
$3.00



2. Input Dimensions

Section	Diameter	Length	Qty
1	0.2500	2.3750	1
2	0.1875	6.0000	1
3	0.1250	2.0000	2

Density	Area	Volume	Weight (lbs)
0.0433	0.0491	0.1166	0.0050
0.0433	0.0276	0.1657	0.0072
0.0433	0.0245	0.0491	0.0021

Total Weight (lbs) = 0.0143

3. Number of Mold Operating Time	
Cold Runner Cycle (seconds)	18
Hours Per Shift (hours)	8
Shifts Per Day	1
Days Per Week	5
Weeks Per Year	13.00
Percentage Regrind (10% max)	10%

4. Enter Cycle and Labor Costs	
Cycle Time Savings (10-35%)	15%
Machine Cost Per Hour	$16
Employee Cost Per Hour	$20

5. Initial and Ongoing Costs	
Estimated Hot Runner System Cost	$15,000
Shop Rate Per Hour	$60
Additional Setup Time (hours)	1
Periodic Maintenance Cycle (weeks)	1
Maitenance Time (hours)	1
HRS Power (dollar per kilowatt hour)	($0.35)

OUTPUT

Output Summary		
Weight of Runners (lbs)		0.0143
Total Cost of Runner	$	0.04
Total Time Mold is Run (sec/year)		1,872,000
Number of Cold Runners Molded		104,000
Total Cost of Runners Per Year	$	4,475.24
Total Cost After Regrind	$	4,027.71
Cycle Time reduction Savings	$	1,248.00
Total Hours Machine is Run		520
Total Machine Time Cost	$	8,320.00
Total Employee Time Cost	$	10,400.00
Electrical Power Cost	$	(200.20)
Additional Labor	$	840.00
Gross Savings	$	15,675.71
Gross Expenses	$	15,639.80

Total Savings - First Year!!!	
$	35.91

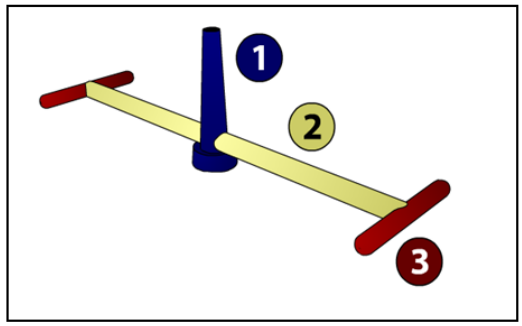
Figure 8-4: Case No. 2 – Financial Feasibility of Hot Runner Mold (4-H Cavity Design)

Another factor that can justify the initial investment in a hot runner system is the high cost of the required polymer. Figure 8-5 illustrates a breakeven in the first year even though the first year production rate was relatively low (16,000 parts). The polymer cost increased from $3 per pound to $65 per pound. This caused a sharp increase in the cost of the runner going up from $0.04 to $0.93 each, an increase of $0.89 per part.

Case No. 3: (1) High cost polymer ($65/lb.), (2) Low production volume (16,000 parts)

INPUT

1. Select Cold Runner Layout
_4H_Cavity
Enter Material Cost/pound
$65.00



2. Input Dimensions

Section	Diameter	Length	Qty
1	0.2500	2.3750	1
2	0.1875	6.0000	1
3	0.1250	2.0000	2

Density	Area	Volume	Weight (lbs)
0.0433	0.0491	0.1166	0.0050
0.0433	0.0276	0.1657	0.0072
0.0433	0.0245	0.0491	0.0021

Total Weight (lbs) = 0.0143

3. Number of Mold Operating Time	
Cold Runner Cycle (seconds)	18
Hours Per Shift (hours)	8
Shifts Per Day	1
Days Per Week	5
Weeks Per Year	2
Percentage Regrind (10% max)	10%

4. Enter Cycle and Labor Costs	
Cycle Time Savings (10-35%)	15%
Machine Cost Per Hour	$16
Employee Cost Per Hour	$20

5. Initial and Ongoing Costs	
Estimated Hot Runner System Cost	$15,000
Shop Rate Per Hour	$60
Additional Setup Time (hours)	1
Periodic Maintenance Cycle (weeks)	1
Maitenance Time (hours)	1
HRS Power (dollar per kilowatt hour)	($0.35)

OUTPUT

Output Summary		
Weight of Runners (lbs)		0.0143
Total Cost of Runner	$	0.93
Total Time Mold is Run (sec/year)		288,000
Number of Cold Runners Molded		16,000
Total Cost of Runners Per Year	$	14,917.45
Total Cost After Regrind	$	13,425.71
Cycle Time reduction Savings	$	192.00
Total Hours Machine is Run		80
Total Machine Time Cost	$	1,280.00
Total Employee Time Cost	$	1,600.00
Electrical Power Cost	$	(30.80)
Additional Labor	$	180.00
Gross Savings	$	15,217.71
Gross Expenses	$	15,149.20

Total Savings - First Year!!!	
$	68.51

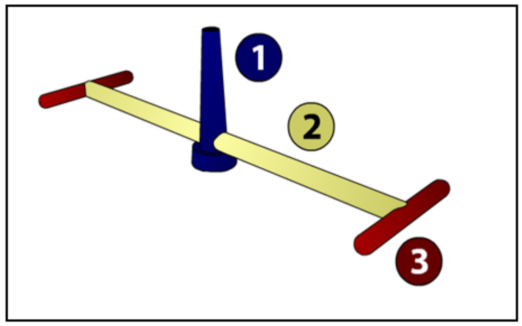
Figure 8-5: Case No. 3 – Financial Feasibility of Hot Runner Mold (4-H Cavity Design)

Justifying hot-runner molds is not just about breaking even. This is just to establish the minimum thresholds required to ensure sustainable profitability. As can be seen in Figure 8-6, when the cost of the polymer was $65 per pound and the production rate remained at 104,000, total first year savings exceeded $83,000. These are some of the financial cases where incorporating a hot runner system would make a wise investment.

Case No. 4: (1) High cost polymer ($65/lb.), (2) High production volume (104,000 parts)

INPUT

1. Select Cold Runner Layout
_4H_Cavity
Enter Material Cost/pound
$65.00



2. Input Dimensions

Section	Diameter	Length	Qty
1	0.2500	2.3750	1
2	0.1875	6.0000	1
3	0.1250	2.0000	2

Density	Area	Volume	Weight (lbs)
0.0433	0.0491	0.1166	0.0050
0.0433	0.0276	0.1657	0.0072
0.0433	0.0245	0.0491	0.0021

Total Weight (lbs) = 0.0143

3. Number of Mold Operating Time	
Cold Runner Cycle (seconds)	18
Hours Per Shift (hours)	8
Shifts Per Day	1
Days Per Week	5
Weeks Per Year	13.00
Percentage Regrind (10% max)	10%

4. Enter Cycle and Labor Costs	
Cycle Time Savings (10-35%)	15%
Machine Cost Per Hour	$16
Employee Cost Per Hour	$20

5. Initial and Ongoing Costs	
Estimated Hot Runner System Cost	$15,000
Shop Rate Per Hour	$60
Additional Setup Time (hours)	1
Periodic Maintenance Cycle (weeks)	1
Maitenance Time (hours)	1
HRS Power (dollar per kilowatt hour)	($0.35)

OUTPUT

Output Summary		
Weight of Runners (lbs)		0.0143
Total Cost of Runner	$	0.93
Total Time Mold is Run (sec/year)		1,872,000
Number of Cold Runners Molded		104,000
Total Cost of Runners Per Year	$	96,963.43
Total Cost After Regrind	$	87,267.08
Cycle Time reduction Savings	$	1,248.00
Total Hours Machine is Run		520
Total Machine Time Cost	$	8,320.00
Total Employee Time Cost	$	10,400.00
Electrical Power Cost	$	(200.20)
Additional Labor	$	840.00
Gross Savings	$	98,915.08
Gross Expenses	$	15,639.80

Total Savings - First Year!!!	
$	83,275.28

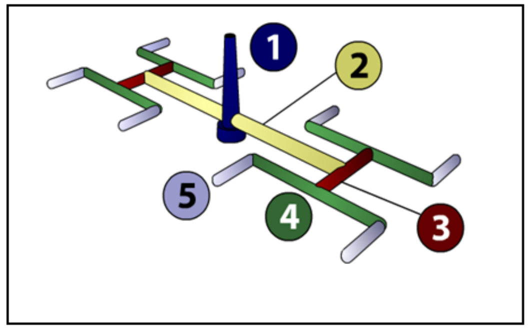
Figure 8-6: Case No. 4 – Financial Feasibility of Hot Runner Mold (4-H Cavity Design)

The previous cases were based on a four cavities 4H runner configuration. If the number of cavities were increased, the material wasted from the runner would increase as well. An example of 8HH runner configuration is shown in Figure 8-7. In this case, breaking even can be reached at a material cost of $40 per pound, which is lower than the $65 used in previous cases. Also, as the weight of the runner increases, so are the savings generated from using hot runner manifolds.

Case No. 5: (1) High cost polymer ($40/lb.), (2) Low production volume (16,000 parts)

INPUT

1. Select Cold Runner Layout
_8HH_Cavity
Enter Material Cost/pound
$40.00



2. Input Dimensions

Section	Diameter	Length	Qty
1	0.2500	2.3750	1
2	0.1875	6.0000	1
3	0.1250	2.0000	2
4	0.1250	2.5000	4
5	0.1250	1.0000	8

Density	Area	Volume	Weight (lbs)
0.0433	0.0491	0.1166	0.0050
0.0433	0.0276	0.1657	0.0072
0.0433	0.0245	0.0491	0.0021
0.0433	0.0491	0.1227	0.0053
0.0433	0.0982	0.0982	0.0042

Total Weight (lbs) = 0.0239

3. Number of Mold Operating Time	
Cold Runner Cycle (seconds)	18
Hours Per Shift (hours)	8
Shifts Per Day	1
Days Per Week	5
Weeks Per Year	2
Percentage Regrind (10% max)	10%

4. Enter Cycle and Labor Costs	
Cycle Time Savings (10-35%)	15%
Machine Cost Per Hour	$16
Employee Cost Per Hour	$20

5. Initial and Ongoing Costs	
Estimated Hot Runner System Cost	$15,000
Shop Rate Per Hour	$60
Additional Setup Time (hours)	1
Periodic Maintenance Cycle (weeks)	1
Maitenance Time (hours)	1
HRS Power (dollar per kilowatt hour)	($0.35)

OUTPUT

Output Summary		
Weight of Runners (lbs)		0.0239
Total Cost of Runner	$	0.96
Total Time Mold is Run (sec/year)		288,000
Number of Cold Runners Molded		16,000
Total Cost of Runners Per Year	$	15,299.95
Total Cost After Regrind	$	13,769.95
Cycle Time reduction Savings	$	192.00
Total Hours Machine is Run		80
Total Machine Time Cost	$	1,280.00
Total Employee Time Cost	$	1,600.00
Electrical Power Cost	$	(30.80)
Additional Labor	$	180.00
Gross Savings	$	15,561.95
Gross Expenses	$	15,149.20

Total Savings - First Year!!!	
$	412.75

Figure 8-7: Case No. 5 – Financial Feasibility of Hot Runner Mold (8-HH Cavity Design)

8.2.2 Modular Melt Modulation Ownership Cost

Product development is often lengthy and costly. Recurring and non-recurring costs can impact the final outcome of any product. It is critical for a product to be low cost and have a simple cost structure prior to launch. While trying to prove the concept, the melt modulation prototype was built using mostly “off the shelf” items. However, there are some expensive components that were bought at retail price. Table 8-1 shows the unit cost of the melt modulation of up to four valve system.

Table 8-1: Cost of Materials for 1 to 4 Valve Modular Melt Modulation Prototype

S/N	Cost/ea.	Description	1 Valve	2 Valves	3 Valves	4 Valves
1	$35.25	Valve Assembly	$35.25	$70.50	$105.75	$141.00
2	$164.98	Actuator Assembly	$164.98	$329.96	$494.94	$659.92
3	$37.99	Voltage Regulator	$75.98	$113.97	$151.96	$189.95
4	$119.00	Power Supply	$119.00	$119.00	$119.00	$119.00
5	$1,495.00	Kistler Pressure Transducer	$1,495.00	$1,495.00	$1,495.00	$1,495.00
6	$249.00	Kistler Pressure Amplifier	$249.00	$249.00	$249.00	$249.00
7	$81.69	Microcontroller & 5" LCD Touch Panel	$81.69	$81.69	$81.69	$81.69
8	$16.09	Motor control Board	$16.09	$16.09	$16.09	$16.09
9	$3.67	Housing (Material total weight 540g at $3.67/kg)	$3.67	$3.67	$3.67	$3.67
10	$36.45	Motor Mount Bracket (Multipurpose 6061 Alum, Rectangular Bar, 1-1/2" x 5" x 6" Long)	$36.45	$36.45	$36.45	$36.45
11	$3.49	5k potentiometer	$3.49	$3.49	$3.49	$3.49
12	$3.49	Control knobs	$3.49	$3.49	$3.49	$3.49
13	$12.60	Mounting Hardware	$12.60	$12.60	$12.60	$12.60
		Total Cost	**$2,296.69**	**$2,534.91**	**$2,773.13**	**$3,011.35**

The biggest costs drivers are the pressure transducer, pressure sensor amplifier, actuators, power supply and voltage regulators. As shown in Table 8-2, the pressure transducer is half of the cost of the 4-valve system. Newer injection molding machines, from 2007 and up, are equipped with the ability to directly export and stream data about the process such as screw speed, position and pressure information. Although the prototype unit has a pressure transducer, if the application is installed on newer injection molding machines, the pressure transducer and the amplifier can be removed. This would save a total of $1,744, which is more than 50% of the cost of 4-valve system and more than 75% of the cost of the single valve system. To make sure that the retrofit market of older injection machines is not ignored, a lower cost of $189 pressure transducer system has been identified. This generates a total saving of $1,555.

Another possibility for cutting down production cost is to redesign the main board to allow for built-in voltage regulators. This would eliminate the cost of the five BEC-5-50 voltage regulators. Also, lower cost power supply and actuators are required. All of these cost reductions would improve the chances of success of the modular melt modulation system drastically. Based on recent quotes received directly from manufacturers, a 4-valve system with pressure sensor cost could drop down to $950 (or $795 for a system without pressure sensors).

Table 8-2: Bill of Materials for Modular Melt Modulation Prototype

S/N	Model	Description	Qty. Ea.	Unit Cost Ea.	Extended Amount	% of Total cost
1	HSR-5990TG	Servo Motor	4	$149.99	$599.96	**4.95%**
2	615286	Motor Pinion Gear	4	$14.99	$59.96	0.49%
3	7880K35	Valve Spur Gear	4	$27.02	$108.08	0.89%
4	THX17 1/4	Valve Shaft	4	$3.56	$14.24	0.12%
5	TQ-031	Valve Shaft Lower Thrust Bearing	4	$2.23	$8.92	0.07%
6	TQ-025	Valve Shaft Upper Thrust Bearing	4	$2.44	$9.76	0.08%
7	BEC-5-50	Voltage Regulator	5	$37.99	$189.95	**6.27%**
8	PM3-45	PowerMax Power Supply	1	$119.00	$119.00	**3.93%**
9	6159A	Kistler Pressure Transducer	1	$1,495.00	$1,495.00	**49.36%**
10	5039A222	Kistler Pressure Amplifier	1	$249.00	$249.00	**8.22%**
11	271-1714	5k potentiometer	4	$3.49	$13.96	0.12%
12	274-415	Control knobs	4	$3.49	$13.96	0.12%
13	2760170	EXP300 PC Board	1	$3.49	$3.49	0.12%
14	20-011-D24	Arduino MEGA2560 Micro+5" LCD Touch Panel SD Card Slot + Shield Kit For Arduino	1	$81.69	$81.69	2.70%
15	8975K501	Motor Bracket (Multipurpose 6061 Al., Rectangular Bar, 1-1/2" x 5"W x 6"L)	1	$36.45	$36.45	1.20%
16	ABS	Housing (Material total weight 540g at $3.67/kg) LCD cover = 61g Front cover = 148g Back cover = 135g Top cover = 115g User interface cover = 81g	0.54kg	$3.67/kg	$1.98	0.12%
17	Misc.	Hardware (Mounting , electrical components, etc.)	1	$25.20	$25.20	0.83%
				Total Cost	**$3,030.60**	

8.2.3 Modular Melt Modulation Operating Cost

The modular melt modulation system prototype has actuators and each actuator can draw a maximum current of 4.8A at stall torque and 300mA when idle. The maximum current drawn from the microcontroller, LCD and other electronic components does not exceed 900mA. At stall torque, the modular melt modulation prototype draws no more than a current of 5.7A per valve. To get the kilowatt-hours of the modular melt modulation, we first need to calculate the power of the device. The electric power in watts is the rate at which energy is converted from the electrical energy to mechanical energy in this case. The power of the device is the product of the applied voltage (V) and the electric current (I) and is given by the following equation:

$$P = VI \tag{8-1}$$

At 6V, the prototype has an electric power that does not exceed 34.2 Watt per valve. In terms of operating cost, the kilowatt-hours of the system can be calculated using the following equation:

$$Cost\ of\ electricity = \frac{Wattage\ x\ hours\ used\ x\ price\ per\ kWh}{1000} \tag{8-2}$$

Assuming that the price per Kilo-Watt-hour is \$0.15, the cost to operate the prototype should not exceed \$0.005 per valve per hour.

8.2.4 Hot Runner Versus Modular Melt Modulation System

Every technology has its own unique set of capabilities and limitations. One way to see these at a glance is to compare technological innovations side by side. Table 8-3 compares the different levels of control that can be achieved during an injection molding cycle, as well as the benefits and disadvantages of each system.

Table 8-3: Comparison of Cold Runner with and without Melt Modulation and Hot Runner Molds

Capability	Traditional Cold Runner Mold	Modular Melt Modulation System	Hot Runner Manifolds System
Melt Flow Control	✗	✓	✓
Multi-cavity	Special tooling required	✓	✓
Family molding	Special tooling required	✓	✓
Weld-line position	Special tooling required	✓	✓
Packing Processing Parameters Control	✗	✓	✓
Packing pressure	✗	✓	✓
Packing time	✗	✓	✓
Temperature Control			
Melt temperature	✗	✗	✓
Mold temperature	✓	✓	✓
Time to change mold	Up to 4 hrs.	5-10 min.	Up to 4 hrs.
Purging time	short	short	long
Adding Additives and Changing Color	Easy	Easy	Not easy and additional time is required
Routine maintenance	No	No	Yes
Repair downtime	short	short	long
Cost of 4-cavity system (not including cost of the mold)	$0	$5,000	$15,000
Parts replacement cost	Low	Low	High (more susceptible to breakdowns, leakage and heating element failure)

Although the latest design of the modular melt modular system has not hit the market, the hot runner has been in the market since 1940. It has seen many improvements over the years, but still presents many challenges. Common hot runner problems include the following:

- Lengthy start-up periods required to stabilize melt temperature
- Excessive repair time, which usually includes full disassembly, cleaning and reassembly
- Nozzle drooling and/or not operational
- Sensitivity to clogs: Even with strainers in line, a slight bit of contamination such as dirt or paper from bags, may plug the small gates
- Excessive flash on part
- Burn marks/streaks on part, or near gate
- Excessive tip wear in nozzles when using plastics with high glass fill content
- Gate vestige too large
- Gate freezing off too soon, or during cycle
- Requires fast cycle to maintain melt state
- Flow lines on large flat part
- Bloom on part opposite gate
- Cold slug in part
- Intermittent blockage caused by cold slug, tip fails by trying to extrude through nut
- Plastics sticking to front of bush nut or sprue nut

8.3 Dimensional Analysis:

One of the most useful tools to determine the cost of a system per use or per cycle is to perform a dimensional analysis. There are two costs involved in injection molding: (1) The cost of the mold and (2) the cost of each unit produced, as shown in Figure 8-8.

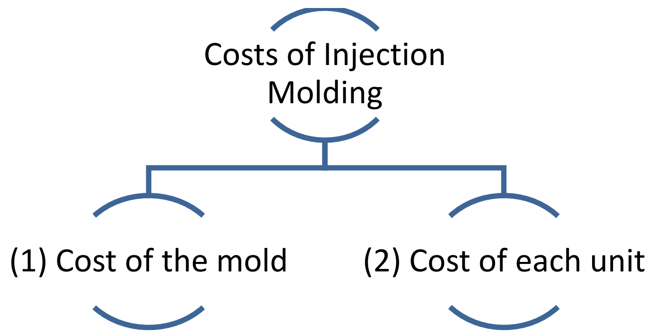


Figure 8-8: Cost of Injection Molding

1) Cost of the mold: The time to build the mold can range anywhere from as little as 50 hours to as much as 500 hours and even more in some extreme cases. There are two methods to estimate the mold cost. The first method is analytical, which estimates the cost of the mold piece by piece. Cost is estimated by multiplying the total number of hours to make the entire mold (i.e. grind, bore, drill, mill, etc.) by labor cost. Since the cost estimate is often required before the final mold construction is defined sometimes before the moldmaker is selected. As a result, this method is not widely used among moldmakers. The second method estimates costs based on several factors including past experience, mold design, relationships with customer and suppliers, and other economic considerations. This method is used more often than the first one.

   To improve the cost estimate, it is convenient to assume the number of working time is 20 hours per day and 50 minutes per hour to allow for a safety margin of 80%. Determining the costs of a particular part depends on several factors including the complexity of the design of the part, the precision required, and the cosmetic effect of the gate. These restrictions usually dictate the number of cavities used on the mold.

Increasing the number of cavities on a mold reduces the total cost of injection molding parts. However, the more cavities you have on a mold, the higher variations in geometry and part physical and optical characters existing between the cavities. The cost of adding additional cavities varies between cold and hot runner systems. For example, adding a second cavity for a cold runner system typically cost approximately 60% more than a single cavity. Increasing the number of cavities using hot runner mold significantly increases the cost in a nonlinear fashion. Adding a second cavity for hot runner would cost about 100% more than a single cavity system and this differential increases with each additional cavity. The primary considerations that impact the mold cost are sales volume, part weight and size, mold cost, and cycle time. As a result, this cost will not be considered in the dimensional analysis.

2) Cost of each unit: This includes the cost of material, machine, and set-up costs. The material cost is based on the amount of the material required to manufacture each part, which typically cost between $1.00 and $3.00 per pound for low cost polymers. The machine time cost is based upon cycle time and number of cavities in the mold and it is widely based on hourly rates that could range anywhere from $20/hour to $75/hour, for automatic operation, depending on the size of machine used. Additional hourly cost can be added if an operator is required. Rates can vary anywhere between

$15-$30/hour. The cycle time is the time it takes the machine to make one mold. The number of cavities indicates how many parts are made from each mold.

To simplify the analysis, all cost for implementing melt modulation system will remain relatively unchanged with the exception of material costs. Focusing only on one of the benefits of the modular melt modulation system provides, family molding while improving parts quality, it is assumed that the acceptance rate of parts molded is 99%.

8.3.1 Cost Analysis

This section will demonstrate the cost analysis of using the melt modulation added per injection molding cycle. To determine the cost of each modular melt modulation system used per cycle, the following assumptions, Table 8-4, were used:

Table 8-4: Assumptions for Dimensional Analysis

ID	Input	Value	Unit
1	Price per 4-valve melt modulation unit	5,000	Dollars Per Unit
2	Life of unit	5	Years Per Unit
3	Working days per year	260	Days per Year
4	Working hours per day	8	Hours per Day
5	Seconds per cycle	36	Seconds Per Cycle
6	Polymer cost per pound	2	Dollars Per Pound of Polymer
7	Pounds per cycle	3	Pounds of Polymer per Cycle
8	Weight per part	1.25	Ounces of Polymer per Part
9	Weight per runner	8	Ounces of Polymer per Cycle
10	Parts per cycle (number of cavities)	8	Parts Per Cycle

The cost added per cycle can be calculated as follows:

Cost Added	One Melt Modulation Unit	Time (seconds)	=	Cost Added
Melt Modulation Unit	Life of the Unit (Hours)	Number of Cycles		Cycle

$ 5000 Cost Added	1 Melt Modulation Unit	1 year	1 day	1 hr.	36 sec.	=	$ 0.005 Cost Added
1 Melt Modulation Unit	5 year	260 day	8 hr.	3600 sec.	1 cycle		Cycle

The cost added per cycle is about half of a penny. If the mold has eight cavities, the cost to own the modular melt modulation per cavity would be $0.005 divided by 8, which is very small.

8.3.2 Cost Savings:

The cost savings is generated from increasing the production rate through multi-cavity or family molding over the life of the melt modulation unit, and it is illustrated in Table 8-5.

Table 8-5: Cost Saving Generated by Amplifying Production Rate

Input Cells
Calculated Cells

Identifier	Input	Value	Unit
1	Cost/unit	5,000	Dollars/Unit
2	Life of unit	5	Years/Unit
3	Working days/year	300	Days/Year
4	Working hours/day	8	Hours/Day
5	Seconds/cycle	36	Seconds/Cycle
6	Cost/pound	2	Dollars/Pound of Polymer
7	Pounds/cycle	1.125	Pounds of Polymer/Cycle
8	Weight/part	1.25	Ounces of Polymer/Part
9	Weight/runner	8	Ounces of Polymer/Cycle
10	Parts/cycle	8	Parts/Cycle
11	Acceptable parts ratio	.95	
	Cost Savings over Unit Lifetime	**$2,565,000.00**	

Over the assumed life of each modular melt modulation system, there is a potential to save over $2.5 million if the system were to be used for five years.

CHAPTER 9 – SUMMARY AND CONCLUSIONS

9.1 Research Summary

Injection molders have long accepted the limitations of cold runner injection molding. As customer demands change, the need for a viable solution to overcome those limitations is becoming more critical. A bleeding edge technology has been developed to meet current market demand. The modular melt modulation system provides the ability to fully control the melt flow and packing processing parameters in real-time during cold runner based injection molding cycles. This system provides an intelligent manufacturing process with the ability to adaptively control part qualities. The technology behind this system is simple. It locally controls the melt flow and packing processing parameters in a mold using mechanical control valves driven by programed servo motors.

The development of melt modulation technology has seen many improvements over the past 10 years. It also has been experimentally validated for several applications of cold runner based injection molding. Previous melt modulation research by Layser [28][32][33] and Tantrapiwat [29][34] demonstrated significant quality product enhancements during the filling phase of cold runner based injection molding, and added capabilities such as balanced multi-cavity molding, family molding, and weld-line position control. Later, Teeraparpwong [35] initiated the investigation of the processing parameters and their impacts on optical properties. The goal was to set the stage for expanding melt modulation capabilities to control packing parameters during the packing phase to enhance product molecular orientation and optical properties. Previously developed systems had many limitations and could only work in a lab setting. The best system was at Technology Readiness Level TRL 4.

The key objectives of this research were as follows:

1. To design and develop an enhanced multi-modular melt modulation prototype with a focus on improved control and commercially viable.
2. To experimentally and analytically validate the enhanced system for novel differential control of filling and packing during injection molding.
3. To scientifically analyze and validate the benefits of a multi-modular system.
4. To complete a thorough engineering analysis exploring the practical business aspects of the new multi-modular system.

All four research objectives have been successfully achieved. As a result of this research, a new and considerably improved modular melt modulation system has been developed and validated through testing. Improvements were not just limited to design and ease of use, but also with capabilities. The new modular system has shown additional capabilities such as controlling packing pressure and time in real-time during injection molding cycle. In addition to improved performance, the new system cost significantly less than the original system and now is commercially viable. The new modular melt system is a stand-alone unit and compatible with most existing cold runner injection machines. It has been validated in the laboratory environment. The laboratory data demonstrated improved value performance in comparison with traditional control methods and data demonstrating effects of different control methods on part quality. This new system has a Technology Readiness Level (TRL) 6.

9.2 Impact of Dissertation Research

While Lehigh University has a strong research capabilities, manufacturing science has been an area where Lehigh has produced critical advances with practical applications. Although some of the advances were just incremental innovations, melt modulation technology is of a different kind. Melt modulation technology is what is considered as radical innovation, which is defined by scholars as an innovation development of a new business or product lines [38].

It is self-evident that radical innovation has been the single, most important component of long-term economic growth. To demonstrate an example of how high strong economy is fueled by innovation, consider the invention of mobile devices. In 1983, when AT&T was being divested in an anti-trust suit, it was considering whether it should attempt to retain the frequencies that would be essential for the operation of mobile phones. As a result, AT&T hired one of America's best-known consulting firms to forecast the likely number of American subscribers for mobile phones by the year 1999. The forecast that was given to AT&T was that there might be as many as one million subscribers. It turned out that the number exceeded 70 million subscribers in that year [39]. In fact, the number of mobile phones sold around the world in late 2010 exceeded 5 billion units [40].

To have more appreciation for innovation, imagine how life would have been now if AT&T had not relied on innovation to pursue the development of mobile phones. Where would the economy be if we had not seen the contribution of companies like IBM, Google, Yahoo, Ebay, Apple, Microsoft and other technology giants? Also, if the United

States government had not created an innovative environment, would not the outcome have been completely different?

Also, there is a direct link between innovation and the strength of the economy. To keep up with the pace with the number of people entering the work force for the first time back in 2000, the U.S. economy would have had to generate 21 million jobs. As it turned out, 23.5 million new jobs were created. It is estimated that small business and the entrepreneurs who run them accounted for more than two thirds of those new jobs. Today, U.S. small businesses (firms with 500 workers or fewer) employ more than 50% of the labor force and generate approximately one-half of the nonfarm private gross domestic product (GDP) [41].

Designing and developing a melt modulation system in a way that is viable for commercialization is one of the major impacts of this research. The modular melt modulation system, compatible with all light and medium weight injection molding machines has been successfully designed, tested and validated. Incorporating this system is inexpensive and greatly reduces production cost and set-up cost.

As a result of this research, I was able to contribute to the advancement of the science and technology related to multi-cavity injection molding process as well as the injection molding industry. With the incorporation of a modular melt system, cold runner injection molding machines can have dynamic melt and packing control. Mold filling and packing pressure can be precision controlled at the individual cavity level, which allows for real-time control of the filling and packing of multi-cavity molds. There is also demonstrated potential for the ability to control weld line position (shift to a non-critical area to increase strength) during each cycle and produced balanced filling for multi-cavity applications and family molding.

Previously developed systems had a number of limitations preventing them from being commercially feasible. This significant design improvement coupled with an increased ease of use and retrofit capabilities indicate the newly developed system is now commercially viable.

Commercialization of the modular melt modulation system can benefit the industry in many ways. Here are some of the value propositions for the modular melt modulation technology:

1. Technical:
    - Intelligent manufacturing process with adaptive control
    - Dynamic melt control - give cold-runner machines the ability to control cavity flow, pressure, and weld-line position (shift to a non-critical area to increase strength)
    - Improve mold quality to produce balanced parts
    - Allow for balanced family molding
2. Business:
    - Reduced production time
    - Low tooling cost
    - Amplify production of high quality parts.
    - Foster economic Growth by introducing market driven technology
    - Create a Leadership role for Lehigh by advancing Manufacturing Industry

This research also intends to bridge the gap between an important scientific discovery and its industrial applications. This was achieved with the goal of advancing science and technology to enhance polymer product manufacturing.

The work in this dissertation highlights my contributions to the advancement of the science and technology related to multi-cavity injection molding processes as well as the injection molding industry with the following accomplishments:

1. Designed and developed a modular melt modulation system to precisely control mold filling and packing pressure at the individual cavity level. This system allows for controlling the filling and packing of multi cavity molds in real-time (CHAPTER 4).
2. Validated the impact of packing processing parameters on the quality of injection molding transparent products through numerical analysis and simulation (CHAPTER 5)
3. Completed additional simulations and analysis to demonstrate results showing the effect of melt modulation control on optical properties of clear polymers and their final product quality (CHAPTER 6)
4. Conducted experimental testing of the modular melt modulation system to illustrate and compare results for parts made with different packing controls. The packing pressure control of the modular melt modulation system was experimentally validated and the results are detailed in CHAPTER 7.
5. Performed market analysis and financial feasibility of the modular melt modulation (CHAPTER 8).

Finally, this dissertation had a major personal impact, as well. When I first started my Ph.D., I had an idea of what I was going to investigate and how I would proceed. However, as I began my research, I realized a large number of skillsets would be required for me to produce scholarly work which would be worthwhile reading. Skills I am proud to have gained at Lehigh University include the following:

- Creative and Independent Thinking
- Research
- Component and Machine Design
- 3-D Design software (Solidworks)
- Product Development
- Numerical Simulations Tools (Moldflow)
- Manufacturing:
    - Machining – programming and operating machines (CNC and manual machines)
    - Operating cold runner based injection molding machines
- Project Management
- Publications

The most valuable skill of all is learning how to be patient enough to stay focused on the research in order to achieve the main objectives.

9.3 Proposed Future Work

The current modular melt modulation system prototype is ready to be field tested. Areas where additional work is needed would include business and technical considerations, such as further cost reduction and market survey. Also, the current system has been designed to be retrofitted with existing injection molding machines. Collaboration with injection molding manufacturers to develop an integrated melt modulation system is crucial to the long term success of this technology. Other features and design improvements can also be added to the existing design. For example, currently prototype uses a bulky, expensive power supply and voltage regulators. The electronics, including the circuit boards, can be redesigned to optimize performance and reduce cost.

9.4 Conclusions

According to previous studies reported in [55] and [65], processing parameters can significantly impact the properties of molded product. Parameters such as melt and mold temperature can have a direct impact on the final properties and quality of the molded product. Higher temperature provides the melt flow more relaxation time before it solidifies. Longer relaxation time leads to material with less residual stresses, less birefringence, and less retardation. However, higher temperatures may also degrade the material and lead to a weaker part as well as inducing more volume loss (shrinkage) and deflection.

The melt modulation control valve has a direct impact on the final quality of a cold runner injection molding products. Turning the valve during the packing phase tends to increase pressure drop across the valve and volume shrinkage, but decrease warpage. Other parameters such as packing pressure and packing time also affect product quality. Increasing packing parameters tends to reduce volume loss (shrinkage) and deflection. However, it increases the product final weight. In addition, increasing packing pressure and packing time causes higher molecular orientation, which is evidenced through higher birefringence and optical retardation. Products with higher molecular orientation in the flow direction exhibit higher tensile strengths. However, high birefringence causes poor optical characteristics such as haze or focal blur.

The two main factors that determine the quality of an optical polymeric product are final geometry and optical isotropy. Because there is no one parameter that can optimize both factors, there is a compromise when controlling processing parameters for maximizing product quality. In other words, manipulating packing parameters to achieve better product geometry is very likely to cause poor optical characteristics and vice-versa. In an effort to overcome these challenges in cold runner based injection molding, future testing will employ the melt modulation system to manipulate the packing parameters to achieve both quality aspects so that the machine will produce a final optical product with optimum quality.

According to the simulations and experimental results, the modular melt modulation system was successfully validated for cold runner injection molding applications. It has the ability to accomplish what similar technologies developed for hot-runner injection molding machines have achieved, but is significantly simpler to use and less expensive to own and operate. The modular melt modulation system provides many benefits to existing cold runner injection molding machines and here are some of them:

- Better control – it provides precise melt flow and packing pressure control of each cavity in real-time.
- Superior part optical quality
- Easy installation and setup - fully integrated stand-alone system with user interface touch screen LCD. No personal computer (PC) is required
- Process repeatability – consistency of shot-to-shot and part-to-part injection molding
- Clean, quiet and energy efficient

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VITA

Majed Alsarheed has over 15 years of industrial experience including the start-up and operation of his own aviation consulting and distribution company. Prior to joining Lehigh, Majed worked for several major Aerospace companies in the United States, leveraging his substantial experience in project management as well as design and development of aircraft equipment. Through his significant background in design and analysis, Majed has managed multi-million dollar projects from conception to delivery.

Majed holds a PhD in Mechanical Engineering from Lehigh University, where he also served as a mentor and Teaching Assistance for the Lehigh Entrepreneurship program. He received his MS in Mechanical Engineering from the University of Pennsylvania, in Philadelphia, PA.